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THE USE OF LENGTH COMPOSITION DATA IN FISH STOCK ASSESSMENTS (WITH NOTES ON VPA AND COHORT ANALYSIS)

by

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Abstract

Methods are described of using data on the length composition of commercial catches as a substitute for age-data in studying the dynamics of fish stocks, and in assessing the long-term effects of changes in fishing pattern. Particular attention is given to the extension of cohort and virtual population (VPA) techniques to length-data, and a brief description of the methods of application of VPA to age-data is also given.

PREFACE

The traditional techniques of stock assessment and the study of the dynamics of exploited fish populations, as developed in the advanced countries around the temperate waters of the North Atlantic and North Pacific rely to a large extent on information on the ages of the fish. In these waters this can for most species be obtained routinely from the examination of large samples of otoliths or scales. In tropical waters this has not proved easy. The absence, in many areas, of big seasonal differences means that there are few clear markings at annual intervals on otoliths or scales. Recent daily rings have been found on the otoliths of a number of fish, but this technique has not yet reached the stage where it can be used for large-scale sampling in most tropical fisheries.

This paper examines ways in which the disadvantages of having no age-data can be overcome by the use of length-data. Particular attention is paid to modifying the techniques of cohort-analysis, or virtual population analysis (VPA) so that they can be applied to length-data. The VPA technique is now widely used in providing management advice in the North Atlantic, but the description of the techniques used are mostly in documents which are not easily available outside the North Atlantic. The first part of this paper therefore gives a brief description of the method.

There are problems in using length-data and, at least as developed so far, there are many things that can be done with age-data that cannot be done with length-data alone. For example, it is not possible to follow the same clearly identifiable group of fish (a cohort or a year-class) through its life in the fishery. It is, however, believed that the techniques presented here will be found useful by any scientists with no age-data, and in particular by those scientists in developing countries who are facing urgent demands to assess the stocks of fish off their coasts. At the very least these techniques should be found useful as supplements to, and checks on, assessments made in other ways, e.g., analysis of catch and effort data.

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1. INTRODUCTION

For some species it is not possible to determine the age of the individuals, so that age-based stock assessment techniques cannot be applied. However, length composition data can be used, instead of age composition data, by first making some assumption about the form of the relationship between length and age.

This manual is concerned with ways of doing this, and in particular with a modification of cohort age analysis (Pope, 1972) for application to length compositon data.

2. ANALYSIS OF AGE COMPOSITION DATA

The methods described below are based on modifications of well-established assessment techniques used for dealing with age composition data. It is appropriate therefore to consider first the basic principles used for age composition analysis, and then to consider modifications of these for handling length composition data.

2.1 The Beverton and Holt Model

A model that is widely used for analysing age composition data is that due to Beverton and Holt (1957). Features of the Beverton and Holt model are that the life history is treated in two parts, and that the part of the life history from "recruitment" onwards is sub-divided into age groups.

2.1.1 Life history in two parts (Fig.1)

Different life history stages are treated separately. In particular the stage from egg to recruitment is treated separately from the remainder of the life history from recruitment to egg production. The model is concerned principally with that part - labelled "stock" in Figure 1 - of the life cycle after recruitment, and Fig.1 shows the basic model in terms of numbers. It is assumed that stock number remains constant so that in the long term

$$R = M + C \quad \text{_ _ _ _ _ _ _ _ _ _ _ _} \quad 1)$$

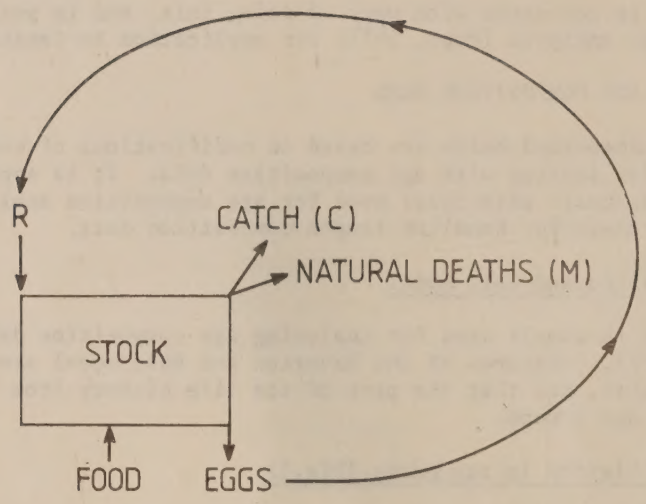
where R = number of recruits (i.e., number of juveniles that join the stock each year)
C = number removed from the stock each year by fishing (i.e., catch)
M = number removed from the stock each year by natural causes (i.e., natural mortality plus emigration).

Immigration from other stocks in not taken into account in this, the simplest form of the Beverton and Holt model. Nor is the model, in its simple form, concerned with the rest of the life cycle, from eggs to recruitment.

2.1.2 Stock subdivided into age groups (Figs. 2 and 3)

In the Beverton and Holt model the stock is subdivided into age groups. The histograms such as Figure 2 can be thought of as showing either: (a) the numbers in a year class at successive ages throughout its life (i.e., numbers against time); (b) the numbers in a stock at any one moment (i.e., numbers of fish of each age or equivalently, numbers in successive year classes). The differences between numbers in the sea at successive ages are equal to the total removals, catches plus natural losses.

Figure 2 can be expanded to describe the whole life cycle under equilibrium conditions (Fig.3). This shows the numbers in successive year classes, all viewed simultaneously at a particular moment in time. The model is visualised as being in a state of dynamic equilibrium. It is dynamic in the sense that the numbers are continually changing (i.e., one year-old fish become two year-old fish, two year-old fish become three year-old fish and



For equilibrium $R = M + C$

Fig.1 The basis of the Beverton and Holt model, showing the division of the entire life cycle into the exploited stock, and the stages from eggs to recruitment.

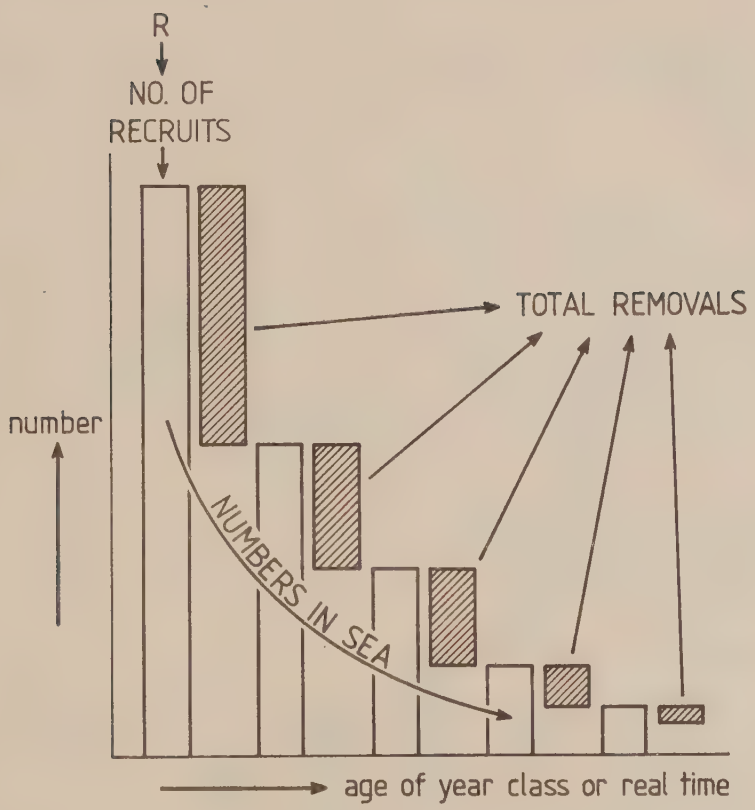


Fig.2 Decreases in numbers of fish in successive ages from recruitment onwards.

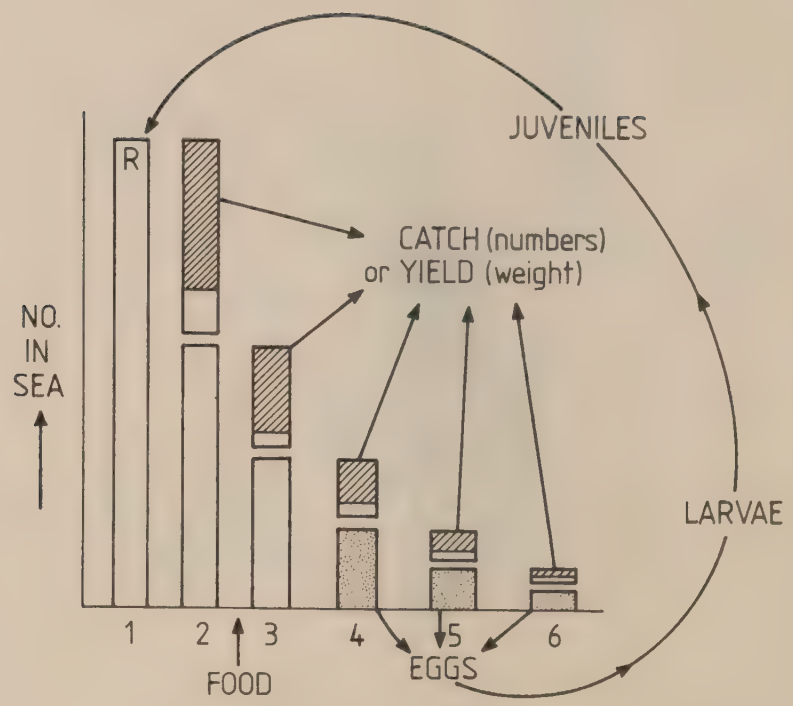


Fig.3 The complete life-cycle for an age-structured model, under equilibrium conditions.

so on). It is an equilibrium in the sense that with constant rates of recruitment and mortality, the basic age composition repeats itself indefinitely year after year.

Total removals are shown, subdivided into catches and natural losses. The numbers along the horizontal axis refer to ages, or year classes. It is only under equilibrium conditions (i.e., when rates of recruitment and mortality are constant) that the sequences of numbers in Figures 2 and 3 happen to be identical.

2.1.3 Virtual population analysis (VPA) (Fig.4)

If it is possible to determine the total number removed from a year class throughout its life, this will provide an estimate of the original number of individuals in that year class. The technique known as virtual population analysis (VPA) 1/ is based on this approach. VPA is, in fact, a procedure for determining how many individuals there must have been in the sea, to account for a known catch and to make an allowance for natural losses also. Theoretical considerations show that this cannot be determined directly from numbers caught but that estimates can be obtained by an iterative procedure or by the use of tables. The basis of the method is described, along with an example in Appendix I.

2.1.4 Cohort analysis

The basis of the procedure to be described later for length composition analysis is known as cohort analysis. It is due to Pope (1972) and is simply a very good approximation to the virtual population assessment technique, that is computationally very much simpler to perform.

Theory is given below, and Section 2.1.5 describes a numerical example.

Cohort analysis is a simple approximation to the virtual population technique (Fig.5). In fish stock assessment theory it is usual to assume that, within any one age group, the decline in number with age follows an exponential curve.

For cohort analysis, the exponential curve within any age group is replaced by a 'step function', by assuming that: (a) the whole of the catch for that age group is taken at exactly the middle of the age interval, and that (b) only natural losses occur continuously on an exponential basis. Pope's cohort formula can then be derived quite simply by proceeding backwards in time from the oldest to the youngest ages.

Thus let N_{t+1} = number in sea at age t+1 (point D in Fig.5)
and let M = instantaneous loss rate due to natural causes
Then by proceeding backwards in time, the number in the sea at the middle of the age interval, just after the catch has been taken, is given by:

$N_{t+1} e^{M/2}$ (point C in Fig.5)

also at the middle of the age interval, but just before the catch is removed, the number in the sea is given by

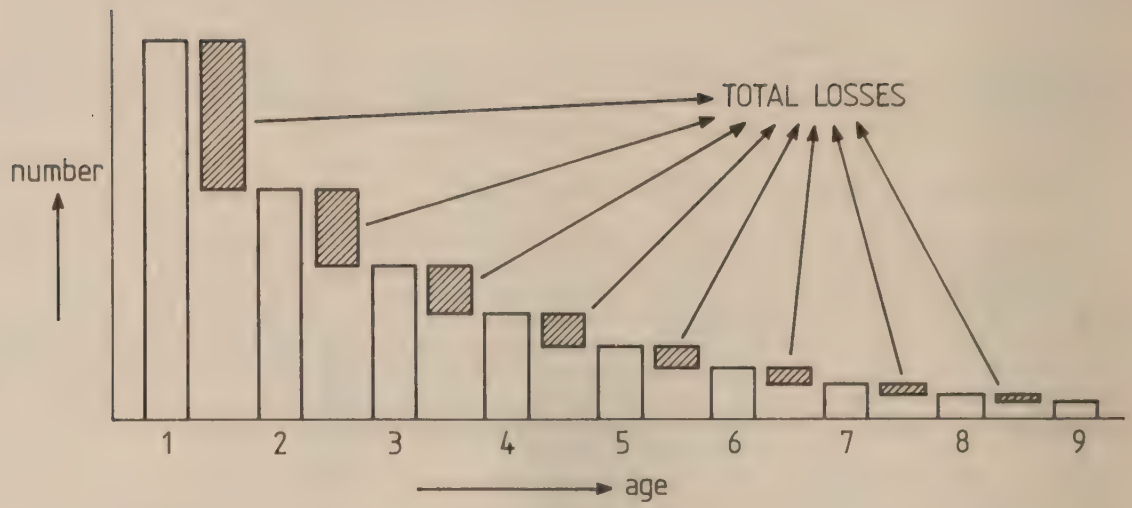
$N_{t+1} e^{M/2} + C_t$ (point B in Fig.5)

where C_t = catch during age interval

Next by proceeding backwards in time one more step to the beginning of the interval, the number in the sea at age t is given by:

$$N_t = (N_{t+1} e^{M/2} + C_t) e^{M/2} \quad \text{- - - - - - - - - - - - 2)} \quad \text{(point A in Fig.5)}$$

1/ The term "virtual population" was introduced by Fry (1957). He used the expression 'virtual population' to describe the sum of the fish belonging to a given year class, present in the water at any given time, that are destined to be captured in the fishery in that year and in all subsequent years.



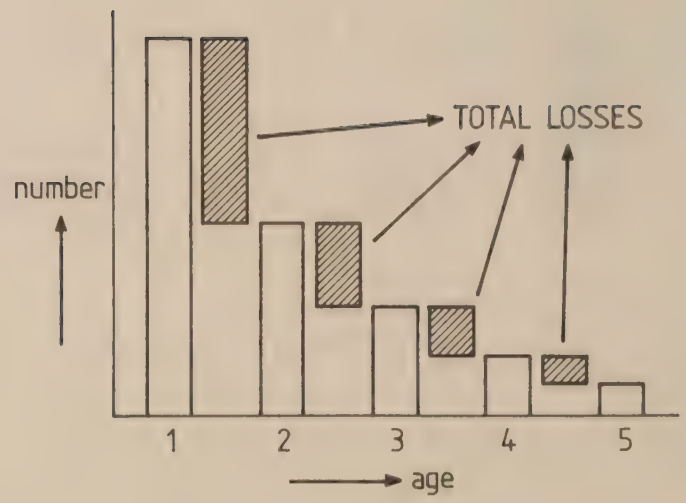


Fig.4 Total removals throughout the life of a year-class must equal the total number of individuals initially present in that year-class. Furthermore this must be so whether there is a low rate of removal (Fig.4a) or a high rate of removal (Fig.4b).

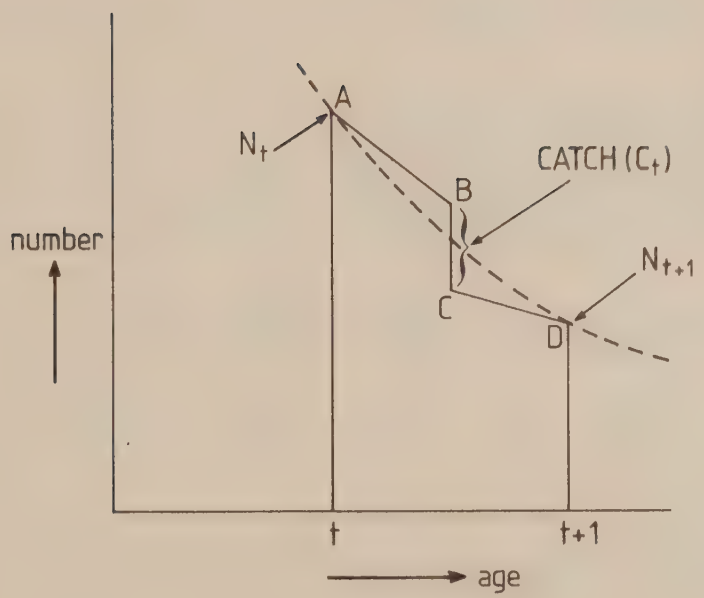


Fig.5 Showing how, in cohort analysis an exponential curve (shown dotted) is replaced by a step function.

where N_t = number in sea at age t

Numerical analysis proceeds by first determining the number in the sea for the oldest age, and then successively applying this formula to determine the numbers in the sea at successively younger ages.

2.1.5 Numerical example of age cohort analysis (Table 1)

A numerical example of age cohort analysis is given in Table 1:

Table 1

Estimation of F and N from the numbers caught in a year class
Cohort Analysis I - Oldest age group (T) consisting of animals aged T and older

Age (t) group	Numbers caught (C_t) (000's)	Numbers attaining each age (N_t)	$S_t = e^{-Z_t}$	Z_t	F_t	Average numbers in sea (000's)
1	867	10097	0.74	0.30	0.10	8707
2	1732	7485	0.61	0.49	0.29	5963
3	1612	4563	0.50	0.69	0.49	3312
4	931	2278	0.45	0.80	0.60	1569
5	362	1023	0.50	0.69	0.49	743
6	153	510	0.55	0.60	0.40	383
7	65	280	0.61	0.49	0.29	224
8 & older	85	170			0.2 *	

*Input number

Total 20901

Input parameters: $M = 0.2$ $F_8 = 0.2$

Calculate $e^{M/2} = 1.105$

1. Calculate N_t for the oldest age group from:

   $N_T = C_T Z_T / F_T$ e.g. $N_8 = 85(0.2 + 0.2)/0.2 = 170$

2. For all younger age groups, calculate N_t from

   $N_t = (N_{t+1} e^{M/2} + C_t) e^{M/2}$

3. e.g. $N_7 = (N_8 e^{M/2} + C_7 e)^{M/2} = (170\ (1.105) + 65)\ (1.105) = 280$ etc.

4. Calculate values of e^{-Z_t} from $e^{-Z_t} = N_{t+1}/N_t$ e.g. $0.61 = 170/280$

5. Calculate values of Z_t corresponding to e^{-Z_t}

6. Calculate successive values of $F_t = Z_t - M$

Summary: for oldest age group (T):

$$N_T = C_T \, Z_T / F_T$$

for younger age groups:

$$N_t = (N_{t+1} \, e^{M/2} + C_t) \, e^{M/2}$$

$$S_t = N_{t+1} / N_t$$

$$Z_t = - \ln S_t$$

$$F_t = Z_t - M$$

Input Data

Principal input data consist of estimates of numbers caught at successive ages (C_t). These can be the numbers at age for a single year class followed through its life (i.e., as in Fig.2). Alternatively these can be numbers at age from a stock exploited under equilibrium conditions (i.e., as in Fig.3). For example in Table 1, 867 refers to the numbers caught between ages 1 and 2 and so on. The final of 85 refers to the catch of individuals aged 8 years and older.

Other input comprises an estimate of M (the instantaneous natural loss rate) and a value of F (the instantaneous fishing mortality rate), for the oldest age group.

Estimation of numbers in sea

The calculation proceeds by starting with the oldest age group and progressing towards the younger age groups.

The first step is to determine the number of fish that must have reached their 8th birthday to account for the catch of 85 individuals aged 8 years and older. This requires values for the natural mortality rate and the fishing mortality rate for individuals aged 8 years and older. In the example the values adopted are:

$M = 0.2$ and $F_8 = 0.2$

The estimate of individuals in the sea at age 8 years (N_8) is given by:

$$N_8 = 85 \, (F_8 + M)/F_8$$

so that: $N_8 = 85 \, (0.2 + 0.2)/0.2 = 170$

i.e., to account for natural losses, as well as the catch of 85 individuals, 170 individuals must have attained an age of 8 years.

Further computations proceed by using the relationship:

$$N_t = (N_{t+1} e^{M/2} + C_t) \, e^{M/2}$$

see section 2.1.4

The value of $e^{M/2}$ is required repeatedly and it is convenient to determine its value first

i.e., since $M = 0.2$, $e^{M/2} = 1.105$

The equation can now be used to determine numbers at each age at successively younger ages.

For example, the number attaining age 7 (N_7) is determined from:

$N_7 = (170(1.105) + 65)\ 1.105 = 280$

Similarly to determine the number that attains age 6

$N_6 = (280\ (1.105) + 153)\ 1.105 = 510$

The computation proceeds in this manner until the value 10097 is reached for the number of individuals that attain age 1.

Calculation of annual survival rates (S_t)

Values of the proportion surviving per year (S_t) can be calculated directly from the value of N_t in Table 1.

For example, from age 1 to age 2 the proportion surviving is 7485/10097 = 0.74. Similarly from age 2 to age 3 the proportion surviving is 4563/7485 = 0.61. In this way values of S_t can be determined for each age interval.

Calculation of the total instantaneous mortality rate (Z_t)

Values of Z_t can be determined from the relationship

$S_t = e^{-Z_t}$ so that

$Z_t = -\ln S_t$

For example, the value of Z corresponding to 0.74 is $-\ln 0.74 = 0.30$.

By proceeding in this manner, instantaneous mortality rates for each age interval can be determined.

Calculation of the total instantaneous mortality rate due to fishing (F)

Values of F for each age interval (F_t) can be determined simply from the relationship:

$F_t = Z_t - M$

for example between ages 1 and 2, $F = 0.30 - 0.20 = 0.10$.

Proceeding in this manner, values of F_t for each age interval can be determined. Note that in Table 1, the final value in the F_t column (i.e., the value of 0.2) is an input value, but that all the other values have been calculated.

Calculation of average numbers in the sea

For any age group, the average number in the sea is given by:

average number $= (N_{t+1} - N_t)/Z_t$

For example, the average number in the sea between ages 1 and 2 is equivalent to:

$(10097 - 7485)/0.30 = 8707$, and so on.

Average numbers should not be confused with numbers attaining each age. Here, for example, 10097 individuals attained an age of 1 year, and 7485 attained an age of 2 years. 8707 is the average number in the sea during the year reaching ages 1 and 2. It is close, but not equal to, the average of the numbers at the beginning and end of the year.

If the input age composition related to a single year class followed through its life, 8707 would be the average number in that year class between ages 1 and 2. If the input age composition related to catches of different year classes taken at the same time, there would be, on the average during the year, 8707 individuals in the first age group (from one year class), 5963 individuals in the second age group (from a different year class) and so on, making up a total stock of 20901 individuals aged 1 to 8 years.

2.1.6 Alternative input age composition data

If the oldest age group consists of one age only (as in Fig.6), the initial computational step should not be as detailed in Table 1. Instead the proportion caught (A) in the oldest age group is given by:

$$A = F(1-e^{-Z})/Z$$

An example is given in Table 2 where the catch in the oldest age group refers to individuals aged from 4 to 5 years. The values of M and F for the oldest age group are given as 0.2 and 0.4 respectively. For the oldest age group:

$$A = 0.4(1-e^{-0.6})/0.6 = 0.301$$

The number at the beginning of the oldest age group is then given from the relationship:

$$N = C/A$$

i.e. $N_4 = 250/0.301 = 831$

The remainder of the calculation then proceeds exactly as in Table 1.

Table 2

Estimation of F and N from the numbers caught in a year class
Cohort Analysis II - Oldest age group (T) consisting of animals aged T only

Age group (t)	Numbers caught (C_t) (000's)	Numbers attaining each age (N_t)	$S_t = e^{-Z_t}$	Z_t	F_t	Average numbers in sea (000's)
1	50	2332	0.80	0.22	0.02	2123
2	200	1865	0.72	0.33	0.13	1573
3	300	1346	0.62	0.48	0.28	1073
4	250	831			0.4 *	
5						

*Input number

Input parameters: $M = 0.2$ $F_4 = 0.4$

Calculate $e^{M/2} = 1.105$

Calculate A_t for the oldest age group

i.e., $A_4 = 0.4\ (1 - e^{-016})/0.6 = 0.301$

Calculate N_t for the oldest age group from $N_t = C_t/A_t$

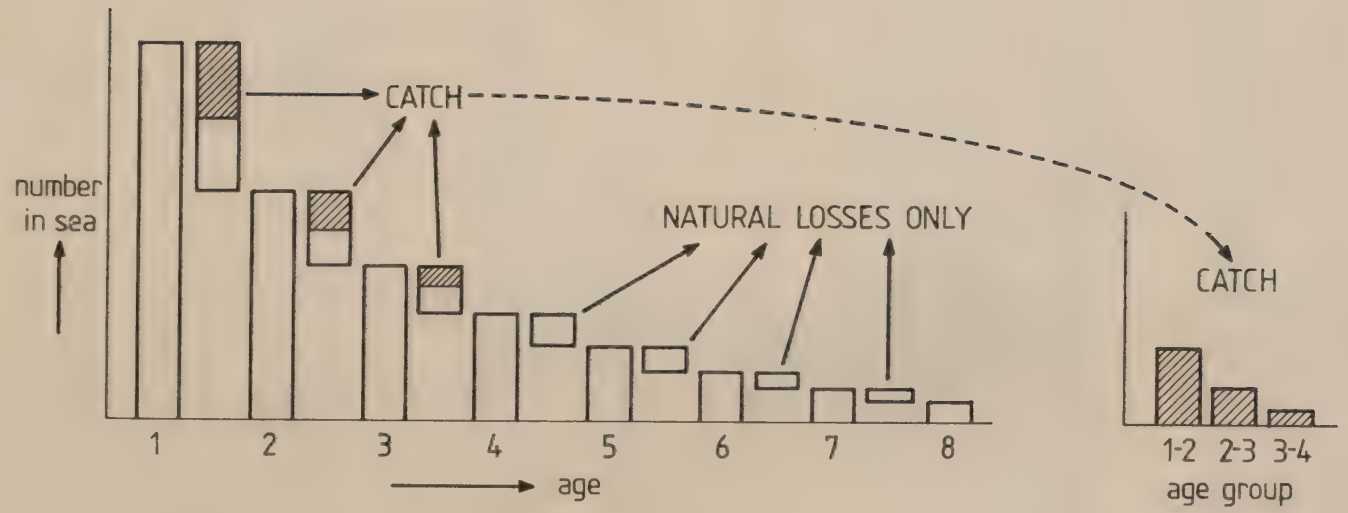


Fig.6 Situation where a year-class is not exploited right up to the end of its life. In this situation there may be a relatively large part of the year-class still alive after the age represented by the oldest age group in the catch.

i.e., $N_4 = 250/0.301 = 831$

Calculate successive values of N_t from

$N_t = (N_{t+1} e^{M/2} + C_t)\ e^{M/2}$ as in Table 1.

Complete other columns as in Table 1.

Summary:

for the oldest age group $N_T = C_T/A_T$

for younger age groups $N_t = (N_{t+1}\ e^{M/2} + C_t)\ e^{M/2}$

$$S_t = e^{-Z}t = N_{t+1}/N_t$$

Note that in this calculation nothing needs to be known about the history of the older age groups, so that this would be an appropriate procedure for dealing with a migratory species, for which the older age groups may not necessarily be present in the fishery.

2.1.7 Comments on input parameters

Value of natural loss rate

VPA (and cohort analysis) are based on the assumption that a relatively large part of the total removals are due to fishing, i.e., it is assumed that information about numbers caught provides useful information about total removals.

If the natural mortality rate is quite unknown, a value may have to be assumed. The calculations are then only likely to be useful if the true value of M is smaller than the value of F. If one is dealing with an intensively fished stock as in Fig.7a, where most of the removals are due to fishing, the numbers caught will represent a substantial proportion of the total losses. In this situation VPA (or cohort analysis) should be a useful technique.

In a relatively unexploited population as in Fig.7b, where F is very small relative to M, the total catch will represent only a small proportion of the total removals, and will provide relatively little information about total removals. In this situation VPA (or cohort analysis) is not likely to be of much value, unless the value of M can be estimated fairly reliably.

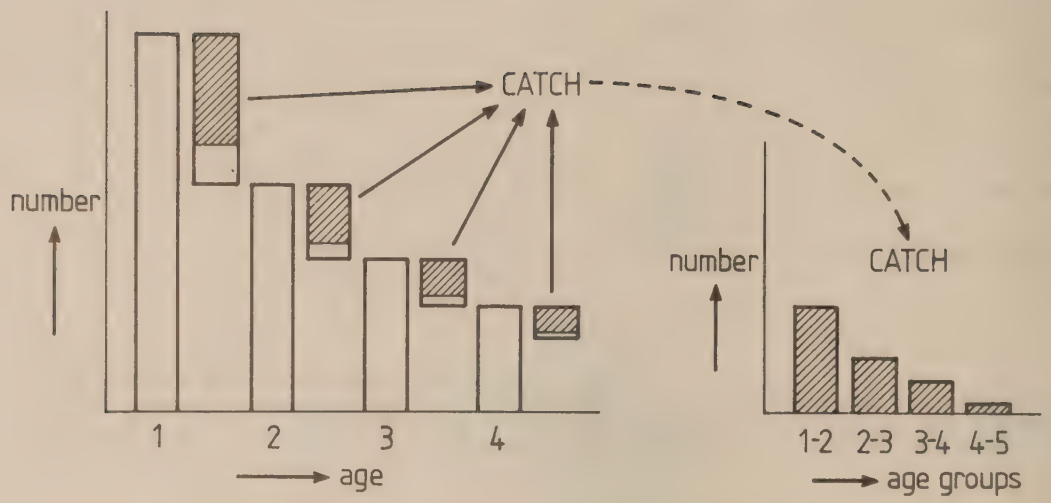
In general, therefore, this kind of analysis is only likely to be useful when dealing with relatively intensively fished stocks, for which the numbers caught represent a relatively large proportion of the total removals.

Figure 8 shows the effect of using different values of M on the calculations in Table 1. In general, as M is increased, the numbers in the sea needed to account for the numbers caught also increases. Also as M increases the estimates of F at each age decrease.

Choice of F and M for the oldest age group

The difference between a lightly fished and a heavily fished stock is further emphasized by consideration of the appropriate input values to use for F and M for the oldest animals.

For example, if the oldest age group comprises all individuals older than a certain age, an input value of F/Z is required (Table 1). The effect on the estimates among the



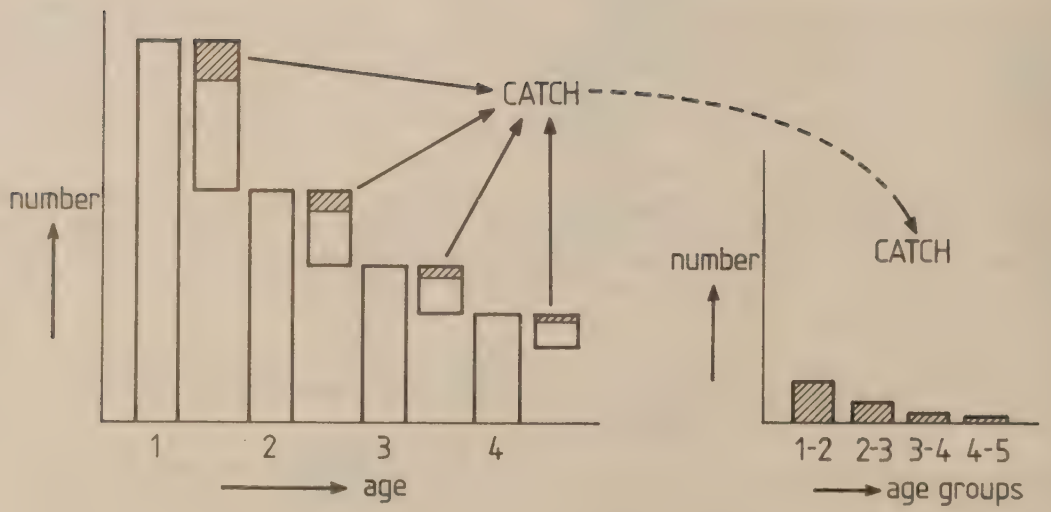


Fig.7 The effect of different rates of exploitation on cohort analysis. If this is high (Fig.7a. above) catches give good information on total removals, but only poor information if exploitation is low (Fig.7b, below).

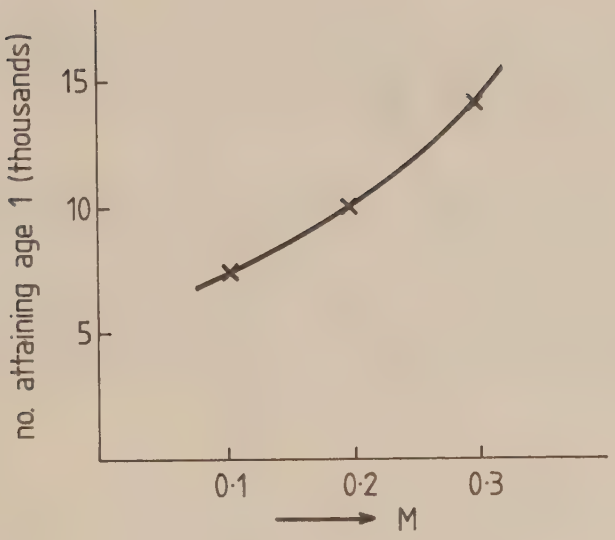


Fig.8 If the computations in Table 1 are repeated using different values of M, different estimates of the numbers attaining age 1 are obtained. Fig.8 shows how, as M is increased, these estimates increase.

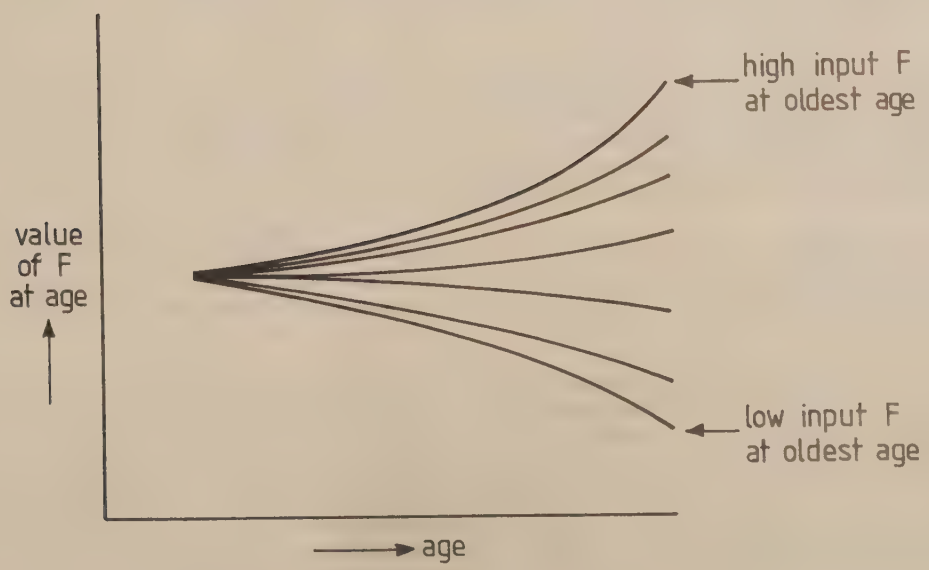


Fig.9 Whatever the input value of F for the oldest age, there is a tendency for the values of F at successively younger ages to converge.

younger ages, of adopting different values for F/Z will depend on whether the stock is heavily exploited or not. If the stock is heavily exploited, the choice of value for the final F/Z is not likely to effect the calculations critically. For example, in Table 1 F/Z for the final age group is 0.2/(0.2 + 0.2) = 0.5. If it is changed to 0.9, the starting value of N_t (i.e., N_8) is changed from 170 to 85/0.9 = 94. If the calculations in Table 1 are repeated, continuing from this value of N_8, it will be found that the results for younger ages are almost identical to those given in Table 1.

Investigations of this kind show that significantly different results only arise when the final value of F/Z becomes very small. For example, if the final value of F/Z is taken as 0.001 (representing a situation in which the animals are very lightly exploited), N_8 becomes 85000, and the subsequent computations become very different from those obtained in Table 1. This means that if fishing accounts for about 50% or more of the total deaths (i.e., if F/Z is in the range 0.5-1), uncertainty about the input value of F/Z is not likely to be critical. On the other hand if a stock is only lightly fished, uncertainty about the input value of F/Z may be very important indeed. If the final F/Z is quite unknown, and also happens to be very small, there may be little point in attempting VPA or cohort analysis.

Iterative solutions

Figure 9 shows the effect of different input values of F, on the subsequent estimates of F at each age. In general, the tendency is for values of F to converge as one approaches the youngest ages.

This suggests that one procedure might be to do repeated calculations for different input F values. The particular calculation for which the input F happens to produce F values at younger ages which behave in some required way might then be adopted as the best choice of input. For example, one might choose a calculation for which the input F happened to equal the average of the F values for the younger ages. More generally, one might prefer a calculation for which the input F happened to be larger, or smaller, by a certain percentage, than the F values for a particular selection of the younger ages. In general, given information (or an assumption) about the way in which F ought to vary with age, it should be possible to find, by trial and error, a solution to satisfy this requirement.

Unfortunately, there is a difficulty with this approach, which is best illustrated by an example. In Table 3, data from Table 1 have been extended to subdivide the number of 8 years and older animals (85) into a catch at age 8 (5 individuals) and a catch of individuals aged 9 years and older (80 individuals). This subdivision has been arranged deliberately so as to introduce an improbably small value for the catch at age 8 years.

For convenience the calculations commence with the same input F value (0.2) for the oldest age group as was used in Table 1. Proceeding with the computations as before, it is seen that the values of F_t and N_t for the younger ages are similar to those obtained in Table 1.

There is one important difference, however, between the results in Table 1 and those in Table 3, and that is the very low value of 0.03 for the value of F for age group 8-9. This is a consequence of the relatively low catch of 8 year-old individuals. Random variations of this magnitude may be particularly pronounced in the input data for old animals since these tend to occur in relatively small numbers. The example shows that such variations can produce correspondingly large variation in the values of F. Because of this, it may not be possible to match input F's to the values of F at younger ages nearly as easily as one might expect. The procedure is always worth trying, but may not always lead to results that are any more useful than those obtained from a non-iterative, single calculation.

Table 3

Estimation of F and N from the numbers caught in a year class
Cohort Analysis III - Oldest age group (T) consisting of
animals aged T and older only

Age group (t)	Numbers caught (C_t) (500's)	Numbers attaining each age (N_t)	$S_t = e^{-Z_t}$	Z_t	F_t	Average numbers in sea (000's)
1	867	10222	0.74	0.30	0.10	8783
2	1732	7587	0.61	0.49	0.29	6004
3	1612	4645	0.51	0.68	0.48	3381
4	931	2346	0.46	0.78	0.58	1624
5	362	1079	0.52	0.66	0.46	792
6	153	556	0.57	0.56	0.36	427
7	65	317	0.63	0.46	0.26	252
8	5	201	0.80	0.23	0.03	178
9	80	160			0.2*	
10 & older						

*Input number

Computational procedure as in Table 1.

2.1.8 Rate of convergence of F values

The rapidity of convergence of F values as one approaches the youngest age group (Fig.9) is a function of total mortality (or, equivalently of survival) from the youngest to the oldest age. It is not, as sometimes supposed, a function of the number of steps involved. The rate of convergence, and hence the reliability of the values for the youngest age group, cannot necessarily be improved therefore simply by dividing the total range into a larger number of intervals. In fact, if there are too many age groups, there will tend to be too few catches per age group, and the problems associated with the kind of variability exemplified in Table 3 will be more likely to arise.

2.1.9 Validity of cohort analysis

Cohort analysis provides an approximation to VPA which, according to Pope (1972) should be satisfactory for values of M up to 0.3 and for values of F up to 1.2. Strictly speaking, however, these values relate to M dt and F dt, where dt is the length of the time interval used - normally one year. This means that for larger values of M than 0.3 or larger values of F than 1.2, the reliability would be by dividing the data of catch-at-age into intervals of less than one year. For very intensively fished stocks, penaeid shrimps for example, it may be appropriate to consider monthly rather than annual catches. This does not necessarily conflict with the comments in section 2.1.8. If total mortality is low, catches will be spread over many years, and it will be appropriate to choose wide age intervals to avoid having too few numbers per interval. On the other hand, if mortality is high, catches will be spread over a short age range, and a subdivision into small age groups should be possible without necessarily leading to too few numbers per age group.

3. ANALYSIS OF LENGTH COMPOSITION DATA

Cohort analysis, and similar methods, enable scientists to understand what is happening to fish stocks by looking at the numbers of fish caught during successive intervals in their lives. In the previous section these intervals have been taken as years, and the data are presumed to have come from the results of large-scale age-determination of samples from the catches. This is not essential. Any method of dividing the whole exploited life-span could be used, and in particular the length of the fish can be used to define the boundaries between successive intervals. The adjustments that need to be made to the procedures based on age-data to make them applicable to length-data are discussed in this section. It will be seen that if the data are considered as representing average conditions, there are no major problems. Each length interval represents a successive interval in the life of the typical year-class, though the duration of the intervals will vary. On the other hand it is extremely difficult to use length-data to follow the fate of one single group of fish during its life in the fishery. With age-data, fish age x in year n are the same as those age x + 1 in year n + 1. It is not possible to identify in the same simple way a constant group of fish in length data from successive periods.

3.1 Theory of length cohort analysis

An important feature of the cohort analysis technique is that each computational step does not necessarily have to apply to exactly one year, or indeed to remain the same from one step to the next. Thus, for greater generality, the basic equation (2) may be replaced by:

$$N_t = N_{t+\Delta t} e^{M \Delta t} + C_t e^{M \Delta t/2} \quad \text{- - - - - - - - - - - -3)}$$

where Δt refers to the time required to grow from the beginning to the end of a length interval. In this form, the equation can be adapted for application to length composition data, providing there is some way of estimating the time required to grow from the beginning of a length interval to the end of a length interval.

There are various ways of allowing for growth, but perhaps the simplest is to make use of the von Bertalanffy equation (Bertalanffy, 1938) which is used very widely in fish stock analysis (Fig.10).

The basic form of this equation is

$$L_t = L_\infty \ (1-e^{-K(t-t_o)}) \quad \text{- - - - - - - - - - - - 4)}$$

where L_t = length at age t

L_∞ = asymptotic length that is attained if the fish is assumed to grow to an infinite age

K is a growth parameter, which determines how rapidly the fish approaches the limiting length L_∞

t_o = intercept on the age of axis corresponding to zero length

Rearrangement of this equation gives an expression for age as a function of length, i.e.

$$t = t_o - \frac{1}{K} \ln (1 - L_t/L_\infty) \quad \text{- - - - - - - - - - - - 5)}$$

This equation can be used to determine the time required to grow from the beginning of a length interval (L_1 cm) to the upper limit of a length interval (L_2 cm).

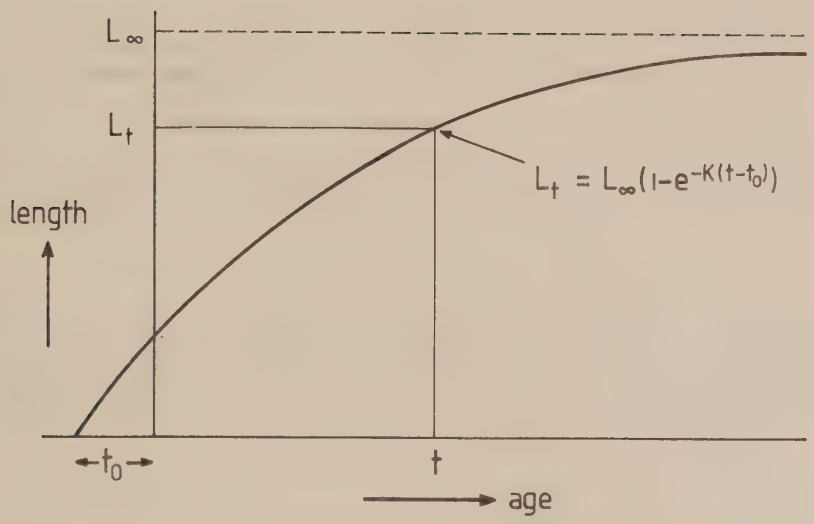


Fig.10 A von Bertalanffy growth curve. The von Bertalanffy growth curve is the function of 3 parameters (L_∞, K and t_o) that is used frequently in fish stock assessments.

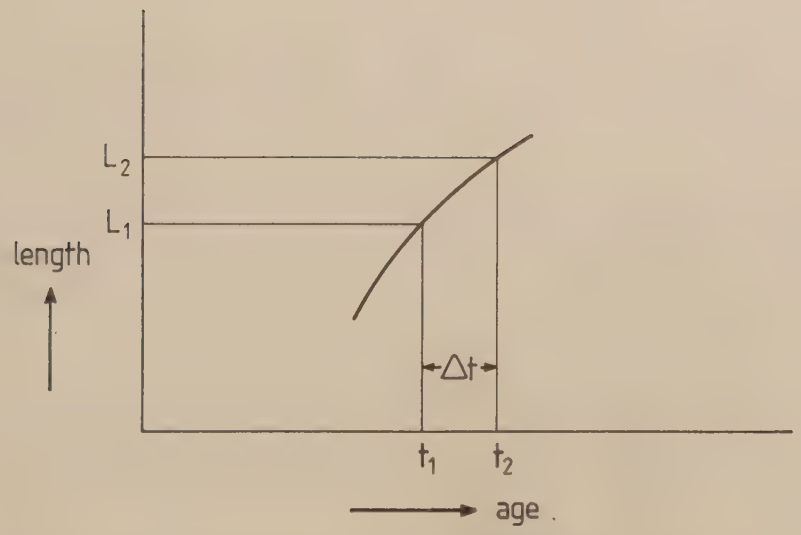


Fig.11 A property of the von Bertalanffy growth curve is that the time required to grow from L_1 to L_2 (Δt), is independent of the parameter t_o.

Thus, if t_1 is the age corresponding to L_1 cm it follows that:

$$t_1 = t_o - \frac{1}{K} \ln (1 - L_1/L_\infty) \quad \text{- - - - - - - - - - - -6)}$$

similarly if t_2 is the age corresponding to length L_2 cm it follows that:

$$t_2 = t_o - \frac{1}{K} \ln (1 - L_2/L_\infty) \quad \text{- - - - - - - - - - - -7)}$$

the time required to grow from L_1 to L_2 cm is therefore simply given by the difference between these equations (Fig.11) and this can be written as:

$$\Delta t = t_2 - t_1 = (1/K) \ln (L_\infty - L_1)/(L_\infty - L_2)) \quad \text{- - - - - - - - - - - -8)}$$

This equation is a function of L_∞ and K but is independent of t_o, i.e., a property of the von Bertalanffy equation is that the time to grow from one length to another is not dependent on the point of origin of the growth curve. This is a useful property and implies that variations in the age interval $(t_2 - t_1)$ for a given length interval $(L_2 - L_1)$ might be expected to be less than the variations in the ages for any given length.

This expression for Δt can be used in conjunction with equation (3) to arrive at a modified equation for analysis of length compositions. Thus, substitution of equation (8) for Δt into equation (3) leads to the following expression:

$$N_1 = (N_2 X_L + C_{1,2})X_L \quad \text{- - - - - - - - - - - -9)}$$

where $C_{1,2}$ is the number of fish caught during a year with lengths between L_1 and L_2 cm and X_L is given by:

$$X_L = (L_\infty - L_1)/L_\infty - L_2)^{M/2K} \quad \text{- - - - - - - - - - - -10)}$$

N_1 and N_2 represent numbers in the sea with length L_1 and L_2 respectively.

This equation is a function of L_∞, M and K. More particularly since the M and the K appear as the ratio M/K, the equation in this particular form is simply a function of the two variables L_∞ and M/K.

We can now proceed, using equation (9) to apply the method of cohort analysis to length data in the same way that equation (3) is applied to age data. The procedure is to first estimate a value for the number of fish reaching the length corresponding to the beginning of the largest length group. Successive applications of equation (9) then leads to estimates of the numbers reaching a particular length for successively smaller animals. An example is given in Table 4.

3.2 Numerical example of length cohort analysis (Table 4)

Table 4 gives a worked example of cohort analysis applied to length composition data. Input data represent numbers caught, classed by length group (column C_L).

Initial input data

Input data include a value of L_∞ (here a value of 80 cm is used), a value for M/K (here = 1.0 is used) and a value for F/Z for the largest length group (here 0.5 is used).

The oldest length group refers to individuals greater than a particular length (here 70 cm and greater) so that for calculating the number at the beginning of this interval it is necessary to know, or to assume, a value of F/Z for this length group.

Table 4

Cohort analysis of the numbers caught in various length groups

Length (L)	X_L	Numbers caught (C_L) millions	Numbers in year class (a) millions	$S_t = e^{-Z\Delta t}$	$Z\Delta t$	F/Z	$F\Delta t$	Z	Average nos. in sea millions
20-25	1.044	0.10	50.46	0.91	0.094*	0.023	0.002	0.205	20.98
25-30	1.049	0.47	46.20	0.90	0.11	0.10	0.011	0.222	23.50
30-35	1.054	3.88	41.53	0.81	0.21	0.50	0.10	0.400	19.50
35-40	1.061	5.54	33.71	0.73	0.31	0.62	0.19	0.526	17.11
40-45	1.069	5.37	24.72	0.67	0.40	0.66	0.26	0.588	13.78
45-50	1.080	4.62	16.61	0.60	0.51	0.70	0.36	0.667	9.90
50-55	1.095	3.03	9.96	0.55	0.60	0.67	0.40	0.606	7.43
55-60	1.118	1.68	5.54	0.53	0.63	0.65	0.41	0.571	4.55
60-65	1.155	1.02	2.93	0.45	0.80	0.64	0.51	0.556	2.88
65-70	1.225	0.46	1.31	0.38	0.96	0.58	0.56	0.476	1.68
≥70		0.25	0.5			0.5			

Input

Assumed values: $L_\infty = 80$; $M/K = 1.0$; F/Z for largest length group = 0.5

Actual values of numbers landed in each length group (C_L)

Steps in computation

1. Calculate values of X_L for each length group from $X_L = \{(L_\infty - L_1)/(L_\infty - L_2)\}^{M/2K}$
   e.g., for the 20-25 cm group

   $X_{20} = \{(80-20)/(80-25)\}^{0.5} = 1.044$

2. Calculate N_L for the beginning of the oldest length group from $C_L/(F/Z)$
   e.g., $N_{70} = 0.25/0.5 = 0.5$

3. Calculate values of N_L for successively smaller fish from $N_L = (N_{L+\Delta L}X_L + C_L)X_L$
   e.g., $N_{65} = \{(0.5)\ (1.225) + 0.45\}\ 1.225 = 1.3$ etc.

4. Calculate values of $e^{-Z\Delta t}$ from $N_{L+\Delta L}/N_L$

   e.g., for 50-55 cm group

   $e^{-Z\Delta t} = 5.54/9.96 = 0.55$

5. Calculate values of $Z\Delta t$ corresponding to $e^{-Z\Delta t}$

   e.g., for 50-55 cm group

   $Z\Delta t = \ln 0.55 = 0.60$

6. Calculate values of F/Z from catch/deaths

   e.g., for the 35-40 cm group F/Z = 5.54/(33.71-24.72) = 0.62

7. Calculate values of FΔt from (F/Z) (ZΔt)

   e.g., for 35-40 cm group FΔt = 0.62 (0.31) = 0.19

   The determination of the values in the last two columns requires additionally a value for M or K.

   Here is assumed that M = 0.2

8. $Z = M/(1 - F/Z)$

   e.g., for 35-40 cm group

   $Z = 0.2/(1-0.62) = 0.526$

9. Average numbers in sea = $(N_L - N_{L + \Delta L})/Z$

   e.g., for the 35-40 cm group

   $(33.71 - 24.72)/0.526 = 17.11$*

* Actual computations done on computer and then rounded off.

Note (a) Data from length-data cannot in general be referred to particular year-classes, but if the data refers to average numbers caught in one year, then the numbers in this column give the average numbers reachinga particular size (the lower bound of the length interval) each year, i.e., they will correspond to the numbers in the average year-class.

To account for the given catch of 0.25×10^6 individuals of 70 cm or more the number in the sea must be:

$0.25/0.5 = 0.5 \times 10^6$

This therefore represents the number that have to attain a length of 70 cm each year to account for the subsequent average annual catch of 0.25×10^6 individuals.

Further calculations

Further computations proceed using equations (9) and (10)

First, values of X_L are calculated using equation (10)

Thus for the 20/25 cm group

$X = \{(80 - 20) / (80 - 25)\}^{0.5} = 1.044$

values of X_L are calculated similarly for all length groups.

Equation (9) can now be used to determine numbers at each length at successively younger lengths. For example, the number that attains 65 cm is given by:

$\{(0.5) \times (1.225) + 0.46\}\ 1.225 = 1.31 \times 10^6$

In this way, estimates of the numbers attaining each length are calculated for successively younger individuals.

Calculation of survival rates

Values of survival rates (S_t) can be calculated directly from the ratios of the numbers attaining successive lengths. For example, for the 60-65 cm length group

$$S = \frac{1.33}{2.94} = 0.45.$$

This is an estimate of the proportion surviving during the time required to grow from L_1 to L_2 cm. It is therefore not necessarily an annual survival rate. The corresponding instantaneous mortality coefficient Z is determined from the natural logarithm, i.e.

$$Z\Delta t = \ln 0.45 = 0.8$$

where Δt is the time needed to grow through the length-interval, in this instance, to grow from 60-65 cm.

Calculation of exploitation rate (F/Z)

Estimates of the exploitation rate, designated by the ratio F/Z, can be determined directly for each length-interval from the relationship:

F/Z = number caught/number dying
for example the 35-40 cm length group

F/Z = 5.54/(33.71-24.72) = 0.62

Calculation of instantaneous fishing mortality rates

Values of $F\Delta t$ corresponding to the fishing mortality rate integrated over a particular time interval is attained from the relationship:

$F\Delta t = (F/Z)\ (Z\Delta t)$
for example for the 60-65 cm length group

$F\Delta t = (0.64)\ (0.8) = 0.51$

Calculation of annual mortality rates

To calculate the annual mortality rates, Z and F, it is necessary to take account of the actual time intervals Δt for each length interval.

This requires additional input information equivalent to separating the ratio M/K into its two separate components; i.e., in addition to knowing M/K, it is also necessary to know either M or K.

For example, if M is given, the total instantaneous mortality rate (Z) can be calculated from the relationship:

$Z = M/(1 - F/Z)$

for example, if M = 0.2, then, for the 60-65 cm length group:

$Z = 0.2/(1 - 0.64) = 0.556$

An estimate of F then follows simply from the relationship $F = Z - M$.

For example for the 60-65 cm length group:

$F = 0.556 - 0.2 = 0.356.$

Calculation of average numbers in the sea

Average numbers in the sea can be calculated from the relationship:

average number = $(N_1 - N_2)/Z$

Thus for the 35-40 cm length group:

$(33.71 - 24.72)/ 0.526 = 17.1 \times 10^6$ [1/]

3.3 Difference between the numbers attaining each length, and the average numbers in the sea

Cohort analysis provides estimates of the average numbers attaining each length during a year as well as of the average numbers present in a length group at any particular moment.

In Table 4 for example, 50.46×10^6 individuals attain a length of 20 cm at some time or other during the course of a year. Some individuals may attain 20 cm at the beginning of the year whereas other individuals may not do so until the end of the year. 50.46×10^6 is the estimate of the number attaining 20 cm irrespective of the moment during the year when this occurs. It is therefore equivalent to the number of recruits at a length of 20 cm. Similarly 46.2×10^6 individuals attain a length of 25 cm irrespective of the time at which this happens during the course of a year.

The average numbers in the sea provide an estimate of the average standing stock of individuals, per length group, under the assumed steady state conditions.

The situation is shown diagrammatically in Fig.12. The shaded part under the curve (n) represents the number in length group (L_1-L_2) under steady state conditions. N_1 is the number of individuals that attain the length L_1 during the course of a year. The rate of entry of individuals into the length group is considered to be at a steady rate N_1 dt. Individuals are lost from the length groups at rates N_2 dt (due to growth) and Z^1dt (due to mortality). If an individual requires more than 1 year to grow from L_1 to L_2 it is possible for n to be greater than N_1, i.e., average number in a length group can be greater than the number attaining length L_1 during any one year.

3.4 Choice of input length composition

For length cohort analysis, it is assumed that the input length composition is representative of a steady state situation, and that the numbers caught represent annual catches per length group. A steady state length composition is not likely to be available in practice. However, a useful approximation can be obtained by determining the average length composition over a period of as many years as possible. In this way the effect of fluctuations in year class strength and mortality rates should be minimised.

There is, therefore, a restriction on the kind of input data for length composition analysis. With age composition analysis it is possible to use either an estimate of the average age composition in any year, or an estimate of the numbers caught from a year class as it progresses throughout its life. Length composition analysis however is restricted to the use of average length compositions.

1/ Calculations in Table 4 have been performed on a computer and then rounded off. Any small discrepancies that may appear are a consequence of repeating the calculations with fewer significant figures.

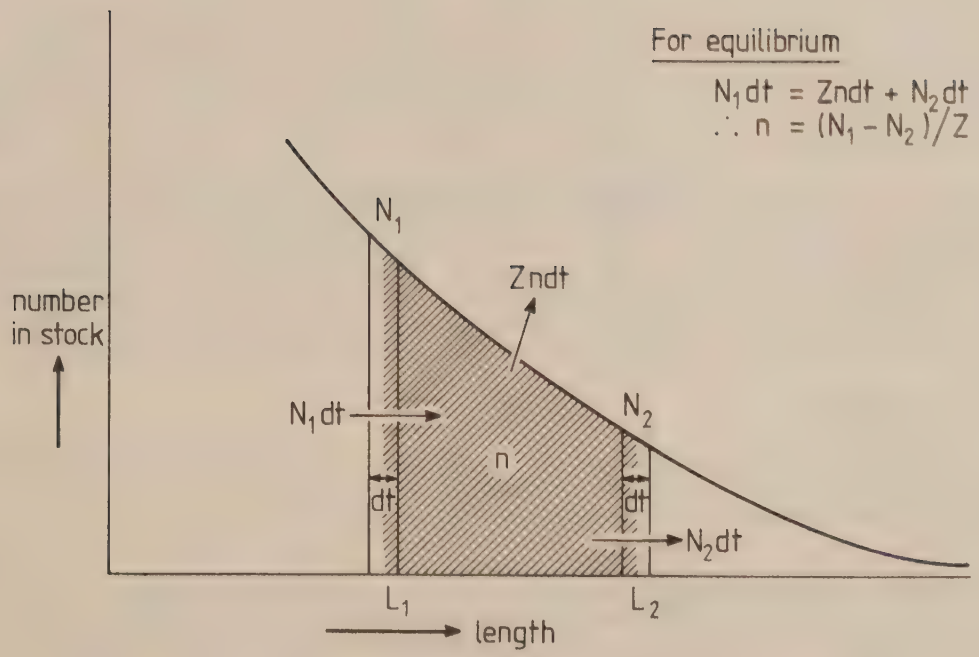


Fig.12 The numbers, n, in a length interval (shaded), and the changes in a short period dt due to growth into and out of the interval, and due to deaths.

3.5 Time and age and relative age in the length composition model

It is useful to be aware of the differences between time, age, and relative age in the length composition model.

Figure 13 shows the relationship between length and real time for a number of cohorts each derived from eggs that hatch on different days. Cohort number 1, for example, may grow from L_1 to L_2 over one time period. Cohort number 4 grows through the same length interval considerably later in real time. The time interval between the different curves depends partly on the different hatching times and partly on different growth rates prior to the attainment of the reference length L_1 cm.

Figure 14 shows the relationship between length and real age for the same cohorts. It is assumed that each cohort is assigned a zero age at the time of hatching. There will be differences in growth rate prior to the attainment of the length L_1 and consequently each cohort will grow from L_1 to L_2 cm over a different age range. The differences in hatching time will be eliminated, however, and one would expect these curves to be much closer together than those in Fig.13, differing only due to differences in growth rate.

Figure 15 shows the relationships between length and relative age for the same four cohorts. By 'relative' age is meant age relative to the age at the time of attainment of a particular length, such as L_1 cm. Over a small length interval it is to be expected that much of the variability would be removed, and that the differences between the various curves would be relatively very small. The cohort length analysis is based on this assumption, i.e., it is assumed that the variation in time needed to grow from L_1 to L_2 cm is small, compared to the variation in the ages or real times involved.

Growth of older fish

For small and medium sized fish it is probably reasonable to assume that there is not a very large variation in the time required to grow through a particular length group. For very large fish, however, this assumption will be less valid.

Figure 16 shows the relationship between length and relative age for a length grouping of large fish. In this situation some individuals may continue to grow throughout the length interval (cohort A) whereas others may actually stop growing and never reach a length of L_2 (cohort B). In this situation the individual variability is clearly very large, and the adoption of an average growth rate to apply to all individuals is only a poor approximation.

To some extent this is compensated by the fact that large individuals usually make up a relatively small proportion of the total catch. Errors, due to the greater variability of growth of the very large individuals, should therefore only apply to a relatively small part of the total population.

3.6 Notes on input parameters

Choice of M/K

A feature of length cohort analysis is that individual values of M and K are not necessarily required. The problem of finding values of M and K therefore simplifies to the problem of finding a value for the ratio M/K. For many fish species, it appears likely that the ratio of M/K is considerably less variable than the individual values of either M or K (Beverton and Holt, 1959; Pauly, 1978). For example, Beverton and Holt, 1959 show that M/K lies largely in the range 0.8 - 2.5. [Also Pauly (1978) from a survey of 122 different stocks of fish concluded that M is related to L_∞, K and temperature T by $M = 0.1228 - 0.1912 \log L_\infty + 0.7485 \log K + 0.2391 \log T$.] If nothing is known about growth, therefore, one procedure might be simply to perform a number of

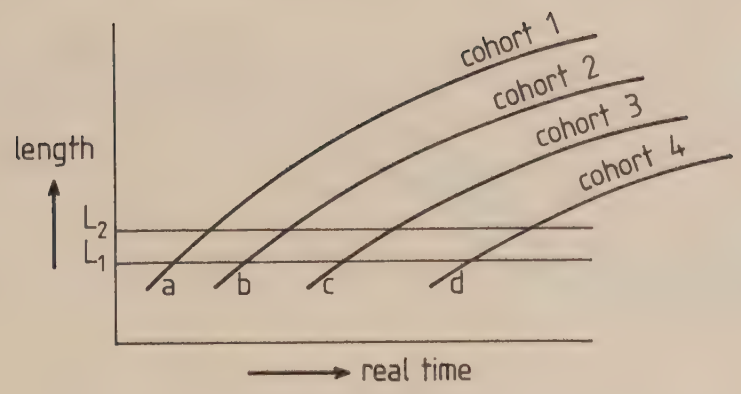


Fig.13 Relationship between length and time for cohorts that commence life at different times.

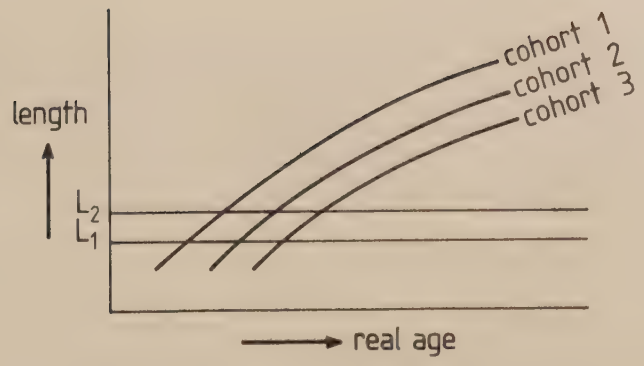


Fig.14 Relationship between length and age for cohorts which all commence life at the same age.

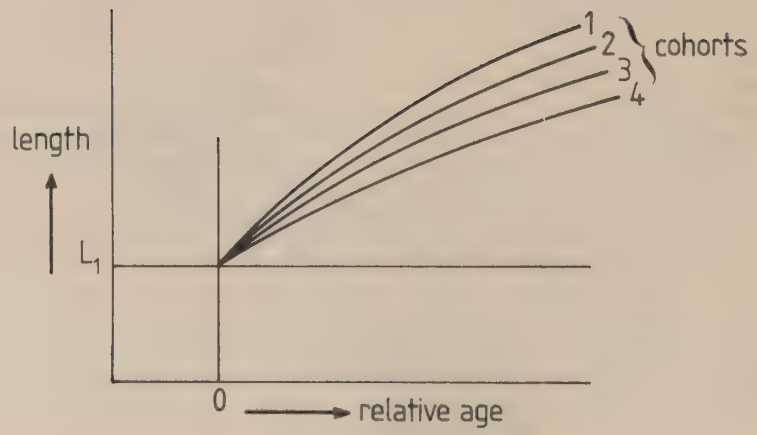


Fig.15 Relationship between length and relative age for cohorts which have the same relative age (here 0) at some specified length (here L_1).

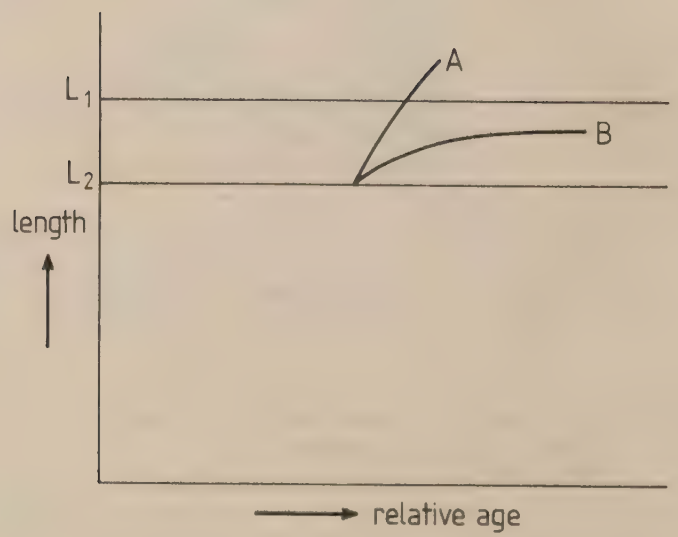


Fig.16 Relationship between length and relative age for large individuals. Within the length group, individual A is still growing but individual B has stopped growing.

calculations using values of M/K ranging from 0.8 - 2.5 (or using values calculated using Pauly's formula).

Another advantage of using a value for M/K is that this should be applicable to species in which some individuals grow more rapidly than the average (i.e., have a high K value) but also experience a relatively high mortality rate (i.e., have a high M value). Another way of thinking of this is to suppose that, in equation (3) it is $M\Delta t$ that is constant and not necessarily M. Thus one individual may grow from L_1 to L_2 quickly, with a high value of M while another does so slowly with a low value of M. The survival rate when growing from L_1 to L_2 may therefore not vary nearly as much as the individual values of M and Δt. Thus when both M and K are unknown, it may be more realistic to vary them together (by using a constant M/K ratio), than to vary them independently and, inadvertently to include combinations of M and K that are biologically improbable.

Choice of L_∞

If nothing is known about growth, a range of values of L_∞ should be adopted. The only restriction need ne that the value of L_∞ must be larger than the length of the largest individuals in the length composition.

Choice of growth parameters (L_∞ and K)

In many instances, and in any event, if further calculations requiring separate values of M and K are required, it is necessary to have a value of K as well as value of L_∞. In this case, it is appropriate to adopt values of L_∞ and K that are compatible with each other. One way of doing this is to relate values of L_∞ and K to a particular growth increment. Even when individuals cannot be aged it is often possible to use the Petersen method, to determine annual growth increments for one or two of the youngest age groups. Compatible values of L_∞ and K can then be determined from a Ford-Walford plot as described below.

In Figure 17 the von Bertalanffy growth equation has been transferred to a straight line by plotting values of length (L_t) at age t against length just one year later (L_{t+1}) at age t+1. This leads to a straight line with a slope of e^{-K} and an intercept on the 45° line of L_∞. Each annual growth increment provides one point on such a line. For example, if animals are known to grow from 21-24 cm in one year, a point can be put on the line with a value of L_t of 21 cm and a value of L_{t+1} of 24 cm. A second point can then be provided by choosing a value of L_∞.

A straight line through those two points then leads to value of L_∞ and K that are compatible with the observed growth increment.

Figure 18 shows an application to a situation where animals grow from 42-46 cm in one year. Then, if L_∞ is assumed to = 70 cm, a straight line can be drawn through point C and through point A. The slope of this line is equivalent to AB/BC.

$= (70-46)/(70-42) = e^{-K} = 0.86$

The value of K is therefore - ln 0.86 = 0.15.

Other lines can be drawn for other values of L_∞. In this way values of L_∞ and K can be obtained that are compatible with the observed growth increment.

If various lines are drawn it is clear that the larger the value of L_∞ the smaller the slope and hence the smaller the value of K. An improbably high L_∞, for example, will be associated with an improbably small value of K. In this situation, it is permissible for the corresponding value of M/K to fall outside the normal biological range.

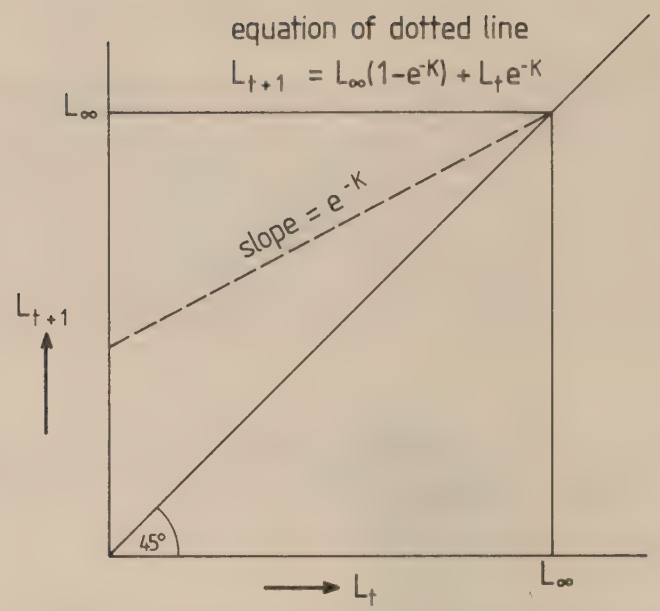
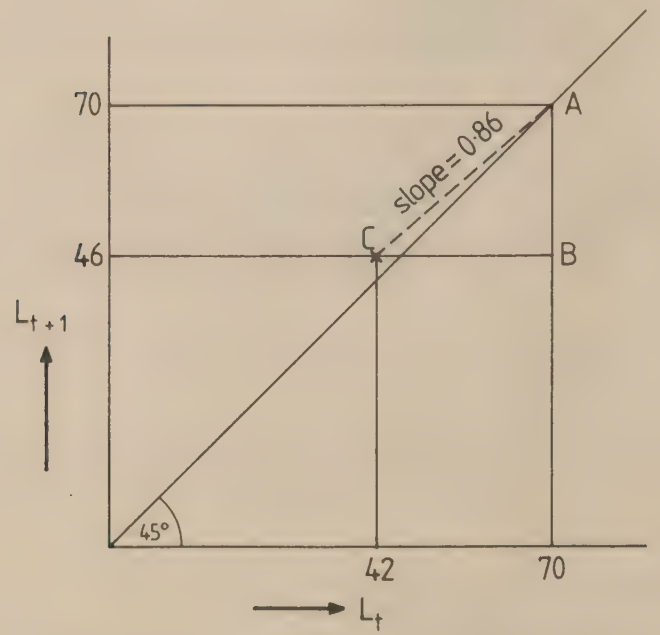


Fig.17 A Ford-Walford plot. The dotted line represents a linear transformation of the von Bertalanffy curve.



$$\text{slope} = e^{-K} = (L_\infty - L_{t+1})/(L_\infty - L_t)$$

$$\text{hence } K = \ln[(L_\infty - L_t)/(L_\infty - L_{t+1})]$$

Fig.18 Use of Ford-Walford plot to relate a given growth increment (plotted at C) to a particular value of L_∞ (plotted at A).

Choice of L_∞, M and K

Because of the various assumptions that might be made about growth and mortality there would appear to be two approaches to the choice of appropriate input parameters for L_∞, M and K.

a) Choose a value of L_∞ that is larger than the largest individuals in the length composition. Choose a value of M/K that is thought to be biologically reasonable for the species concerned.

b) Choose values of L_∞ and K, that are consistent with a given growth increment. Choose a value for M, and calculate M/K from the values of M and K accepting that, in this situation it is permissible for M/K to have an improbable value.

Choice of L_∞ and K for species that can be aged

For species that can be aged it is possible to determine a growth curve directly and, by fitting a von Bertalanffy curve in the usual way, i.e., to the average lengths of each age group, to arrive at estimates of L_∞. These, however, are not necessarily the best values of L_∞ and of K to use, because in reality there are two underlying relationships. One is the relationship between length and age (i.e., corresponding to each age there is a mean length and the relationship between these constitutes a conventional growth curve). With this relationship the value of L_∞ may be smaller than the largest individuals in the length composition (see Fig.19).

The other is the relationship between age and length (i.e., corresponding to each length there is a mean age (see Fig.20). The relationship between these provides a different growth curve with different values of L_∞ and K). With this relationship, the value of L_∞ will not be smaller than the largest length. For cohort analysis of length compositions it is the values of L_∞ and K from this relationship that are required. Consequently, even if the species can be aged, and values of L_∞ and K are available from a conventional relationship of length on age, these are not necessarily the correct values to use.

In this situation the most straightforward procedure is to:

a) adopt a value of L_∞ greater than the largest length sampled, and

b) determine a value of K consistent both with this and with at least one annual increment calculated from the conventional growth curve.

4. LONG-TERM EFFECT OF CHANGES IN FISHING EFFORT AND MESH SIZE

Given output from a length, or age composition cohort analysis (or VPA) it is a comparatively simple matter to extend the calculations to determine the long-term effects of a change in mesh size and/or fishing effort. This can be done using a value of M/K and without necessarily having separate values for M and K. Theoretical details are given in Appendix 2.

4.1 Basic theory

Figure 21a shows the relationship between the steady state numbers-at-length in the catch and the steady state numbers-at-length in the sea for a given pattern of fishing, i.e., values of fishing mortality at each age. Figure 21b shows the comparable length compositions obtained under a different pattern, but starting out from the same number of recruits (R).

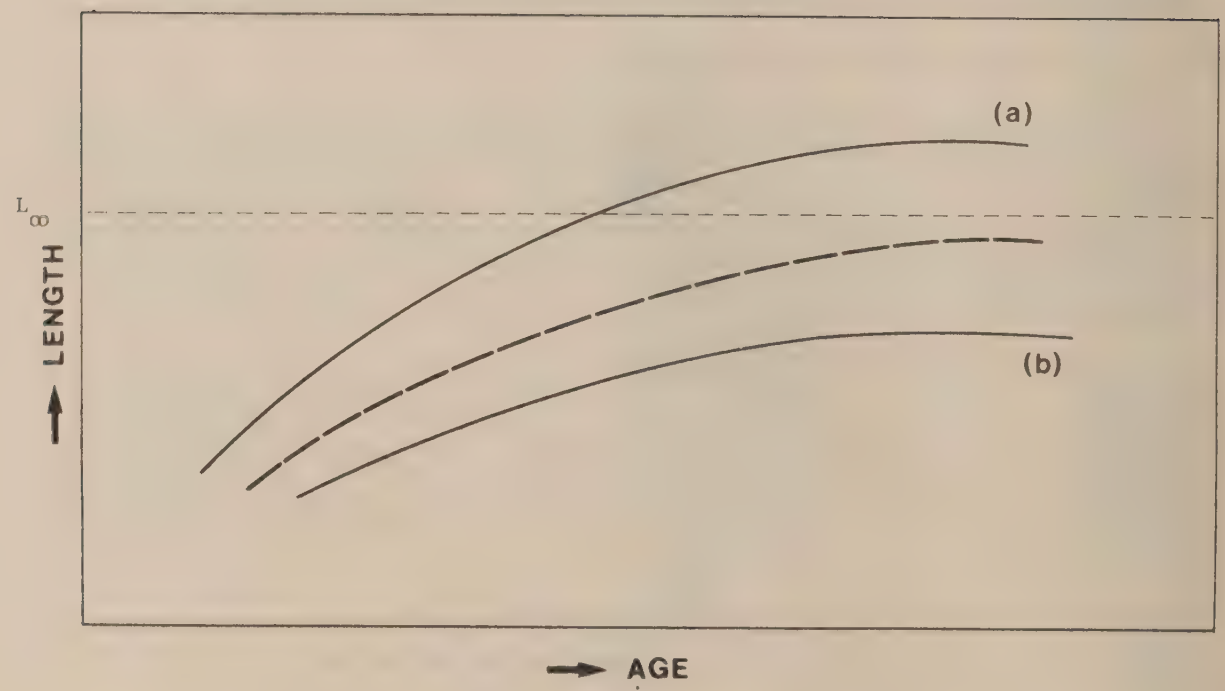


Fig.19 Growth curves for fast growing (a), and slow growing (b) fish, and the relation between average length and age (dotted). The figure shows how some fish can be larger than the L_∞ of the population.

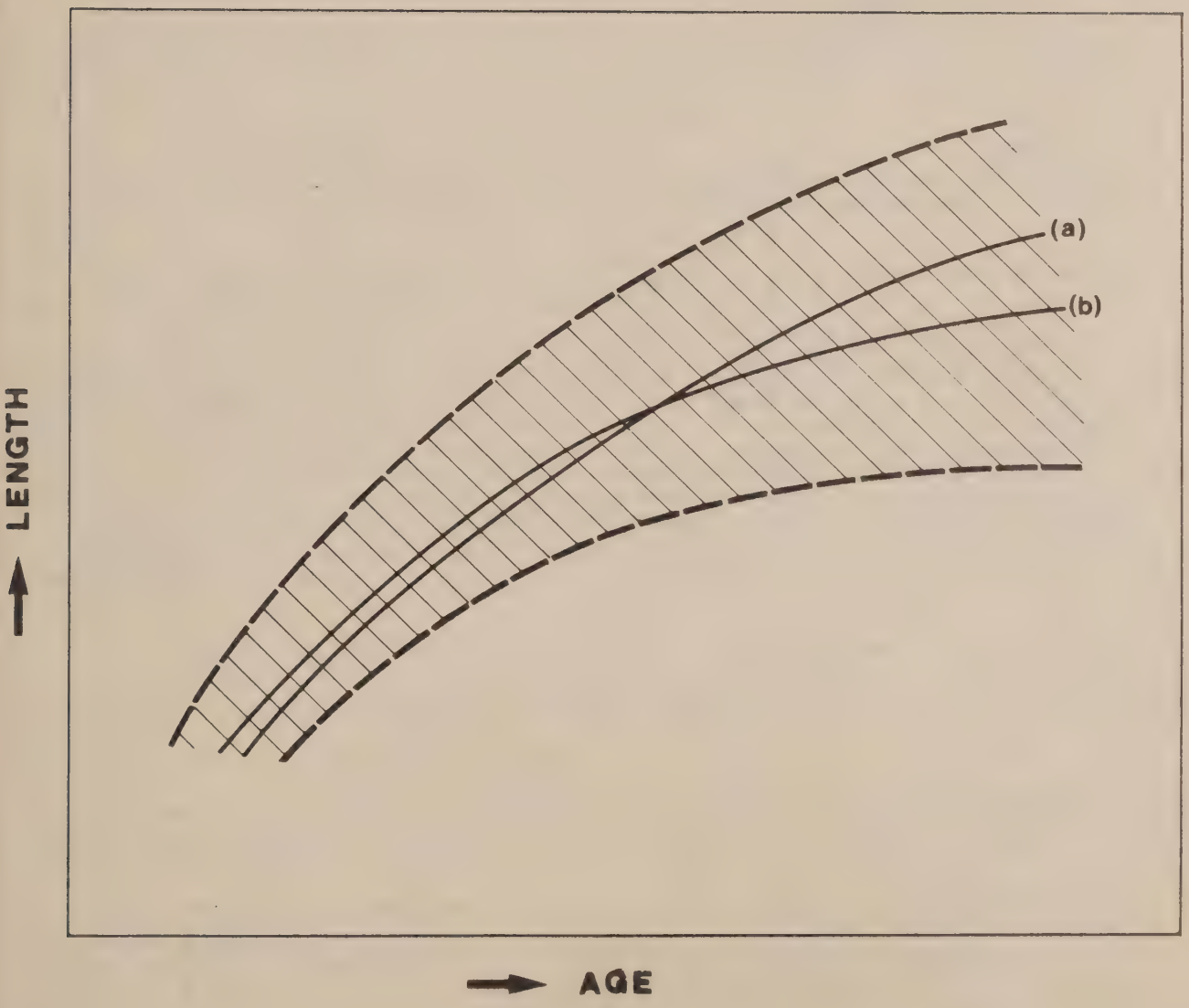


Fig.20 The relation between the average length of fish of a given age (a), and between the average age of fish of a given length (b). The shaded area shows the range of individual growth curves.

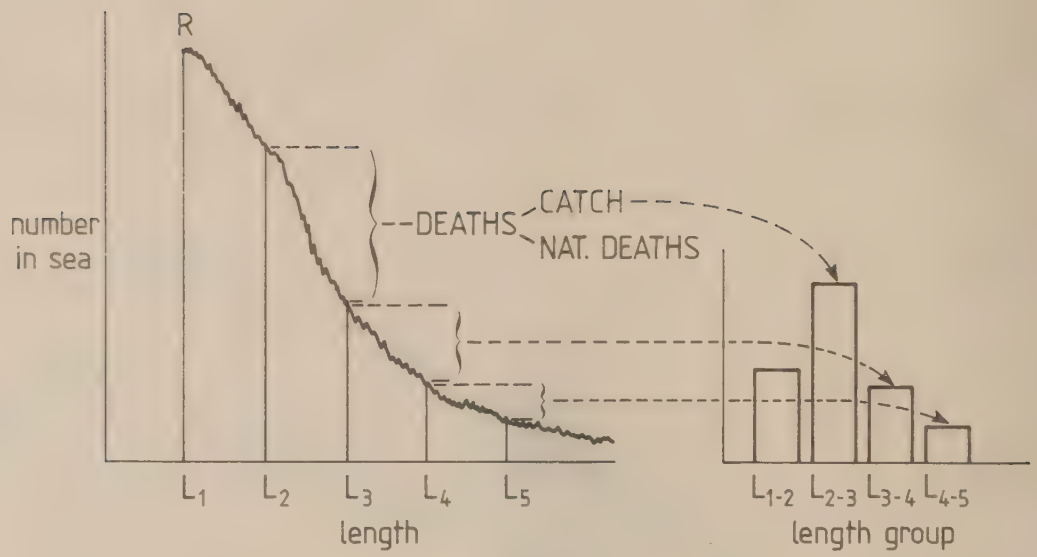


Fig.21a The relationship between the steady state numbers at length in the catch and the steady state numbers at length in the sea

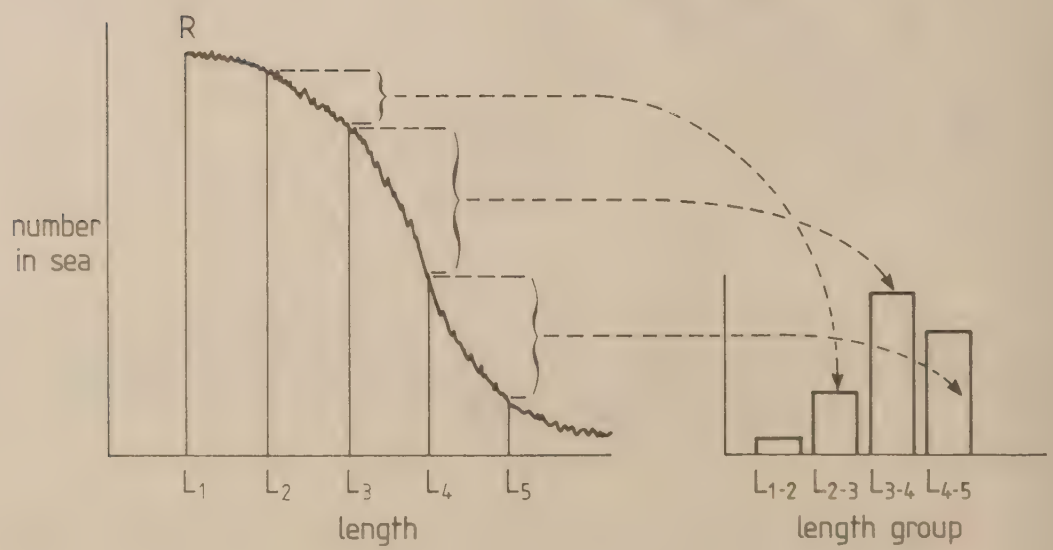


Fig.21b Length composition data, comparable to those in Fig.21a, but obtained under a different pattern of fishing, starting out from the same number of recruits.

If one starts with a length composition of catches, such as that as shown in Figure 21a, the first step is to use cohort analysis to determine the required initial number of recruits (R) at some arbitrary starting length, L_1. The next step is to start with the same number of recruits and to work forward in time, taking account of a new set of conditions (for mortality rates, for example), to arrive at a new steady state length composition of the catch as shown in Figure 21b.

The numerical example given in Section 4.2 is based on this approach, and uses a simple approximation that enables an observed length composition of catch to be converted directly to a predicted length composition of the catch.

4.2 Numerical example

Tables 5 and 6 provide an example (taken from Jones, 1979) of the effect on Nephrops yield per recruit of a 40% increase in fishing effort and an increase in mesh size of 20 mm.

Table 5 shows the input length composition and details of a length cohort analysis carried out in exactly the same way as described in Table 4.

Table 6 shows the further calculations required to take account of the changes in fishing effort, and mesh size. Column 2 is simply a conversion from numbers caught to weights caught at each length. If preferred the input for column 2 may remain in the form of numbers caught. In that case the end point of the calculation would be an estimate of the long-term effect of the change in mesh size and effort, on the total number caught instead of on the total weight caught. Column 3 represents values of Fdt taken from Table 5. Column 4 comprises input data and gives the proportions retained for each length group for the mesh size originally used. Column 5 gives the proportions retained at each length for the new mesh size. Column 6 shows the new fishing mortality rate per length group, taking account of the change in mesh size and effort. This is calculated from the relationship:

$$F_2dt = 1.4S_2 \ (F_1dt)/S_1$$

where S_1 is the proportion retained by the original mesh and

S_2 is the proportion retained by the new mesh.

The equation states that the new fishing mortality rate is equivalent to the old fishing mortality rate increased by 40% (to allow for the change in fishing effort) and adjusted by the ratio S_2/S_1 (to take account of the change in mesh size).

Column 7 shows the differences between the original fishing mortality rates and the new fishing mortality rates. Column 8 shows the differences between the old and the new fishing mortality rates, summed up to the middle of each length group interval. Column 9 shows the values of column 8 raised using the exponential coefficient. The values in this column provide factors for determining the long-term effect of the changes in fishing effort and mesh size on the numbers in the sea. For example for the 20-25 mm length group the factor in Column 9 is 1.0403. This means that after a new steady state situation has been reached, the number (or weight) of individuals in this length group in the sea would have increased to 1.0403 times the previous level. Similarly the other values in Column 9 provide the conversion factors for each of the other length groups.

Column 10 shows the conversion factors for each length group, for converting the original catches (in numbers or weights) to predicted catches (in numbers or weights). Each conversion factor is obtained by multiplying the value in column 9 by $1.4S_2/S_1$; this takes account not only of change in abundance in the sea, but also of the change in catch rate on length group.

Tables 5 and 6 - Estimating the long-term effect of a change in mesh size and fishing effort (from Jones, 1979)

Table 5

Cohort analysis

Worksheet showing sample cohort analysis of length composition data, L_{oo} = 70.0, M/K = 0.400, final F/Z = 0.70, M = 0.20

Length group (mm)	No. caught 1/ (1000)	No. in sea 2/ (1000)	Mean No. in sea 3/ (1000)	F/Z	Zdt 4/	Fdt 4/	Z	dt
65-70	3	4						
60-65	10	17	14	0.778	1.386	1.078	0.900	1.540
55-60	94	122	55	0.896	1.963	1.758	1.916	1.025
50-55	312	467	167	0.903	1.342	1.213	2.070	0.649
45-50	827	1 380	407	0.910	1.079	0.983	2.232	0.484
40-45	1 650	3 190	827	0.909	0.841	0.765	2.196	0.383
35-40	3 040	6 530	1 490	0.911	0.716	0.652	2.239	0.320
30-35	4 730	11 700	2 430	0.907	0.587	0.532	2.145	0.274
25-30	4 120	16 500	3 320	0.861	0.342	0.294	1.440	0.237
20-25	1 390	18 700	3 710	0.652	0.121	0.079	0.575	0.211
15-20	163	19 600	3 640	0.183	0.047	0.009	0.245	0.191
10-15	1	20 200	3 460	0.001	0.035	0.000	0.200	0.174
Total	16 340		19 520					

1/ Length composition of catches.

2/ Estimate of number attaining the lower limit of each length group (i.e., 122 000 attain a length of 55 mm).

3/ Mean numbers in the sea in each length group at any one time.

4/ Values of Z (and F) multiplied by dt, the time required to grow from the beginning to the end of each length group.

COMPUTATIONAL PROCEDURE

1) Calculate the first value of column (2) from
(Number landed)/(final F/Z)
i.e. 3/0.7 = 4.29

2) Calculate a value of "X_L" for each length group
e.g. for the 60-65 mm length group

$$X_L = \left(\frac{L_\infty - 60}{L_\infty - 65}\right)^{M/2K} = \left(\frac{10}{5}\right)^{0.2} = 1.15$$

3) Calculate successive values of N_L (i.e. column 2) from

$$N_L = (N_{L+\Delta L} X_L + C_L) X_L$$

where C_L is the number caught in the length group
L to L + ΔL
i.e. for the 60-65 mm length group the number attaining 60 mm is given by:
{4.29 (1.15) + 10} 1.15 = 17.17 ($x10^3$)

COMPUTATIONAL PROCEDURE (cont.)

(Note that the values shown in the table were calculated using more significant figures).

4) Calculate values of F/Z from the relationship
F/Z = (number caught)/(number dying)
e.g. for the 60-65 mm length group
F/Z = 10/(17.17 - 4.29) = 0.78

5) Calculate Zdt from the relationship
$\exp(-Zdt) = (N_{L+\Delta L})N_L$
e.g. for the 60-65 mm group
exp (-Zdt) = 4.29/17.17 = 0.249
so that Zdt = 1.39

6) Calculate Fdt from
Fdt = Zdt(F/Z)
e.g. for the 60-65 mm group
Fdt = 1.386 (0.778) = 1.078

In order to calculate columns (3), Z and dt a value of M is required. Here a value of 0.20 has been assumed.

7) Calculate Z from
Z = M/(1 - F/Z)
e.g. for the 60-65 mm group
Z = 0.20/(1 - 0.778) = 0.90

8) Calculate dt from
dt = Zdt/Z
e.g. for the 60-65 mm group
dt = 1.386/0.90 = 1.54

9) Calculate column (3) from
mean number in sea = $(N_L - N_{L+\Delta L})Z$
e.g. for the 60-65 mm group
(17.1 - 4.29)/0.90
= 14.23 ($x10^3$)

Table 6

Worksheet showing calculation of effect on yield per recruit of a 40% increase in fishing effort and an increase in mesh size of 20 mm

1 Length (mm)	2 NxW (kg)	3 F_1dt	4 S_1	5 S_2	6 F_2dt	7 F_1dt-F_2dt	8 $\Sigma(7)$	9 exp(8)	10 $\frac{S_2(9)}{S_1}$	11 (2)x(10)
10-15	1	0	0.0019	0	0	0	0	1.0000	0	0
15-20	480	0.0085	0.1170	0.0039	0	0.0085	0.0041	1.0041	0.0469	22
20-25	8 714	0.0792	0.6950	0.1038	0.0166	0.0626	0.0395	1.0403	0.2176	1 896
25-30	47 126	0.2943	0.9864	0.5557	0.2321	0.0622	0.1019	1.1073	0.8733	41 156
30-35	89 290	0.5323	1.0	0.9382	0.6992	-0.1669	0.0495	1.0508	1.3801	123 231
35-40	88 170	0.6520	1.0	0.9984	0.9113	-0.2593	-0.1636	0.8491	1.1868	104 638
40-45	69 660	0.7647	1.0	1.0	1.0706	-0.3059	-0.4462	0.6401	0.8961	62 425
45-50	48 750	0.9828	1.0	1.0	1.3759	-0.3931	-0.7957	0.4513	0.6318	30 801
50-55	24 830	1.2130	1.0	1.0	1.6982	-0.4852	-1.235	0.2908	0.4071	10 109
55-60	9 829	1.7580	1.0	1.0	2.4612	-0.7032	-1.829	0.1606	0.2248	2 210
60-65	1 343	1.0780	1.0	1.0	1.5092	-0.4312	-2.396	0.0911	0.1275	171
65-70	508	1.0780	1.0	1.0	1.5092	-0.4312	-2.828	0.0591	0.0827	42
Total	388 701									376 701

Input Column 2 N = Numbers caught (from Table 5)
W = Average weight (from $W = 0.00055\ L^3$)
e.g. for 25-30 mm size group $NW = 4120 \times 10^3 \times 0.00055(27.5)^3 = 47\ 126 \times 10^3$ g

Column 3 F_1dt = values of Fdt from Table 5

Columns 4 and 5 Estimates of proportions retained at each length by 70 mm and 90 mm meshes using a selection factor of 0.3 and arbitrary ogive slopes

Column 6 $F_2dt = 1.4\ S_2(F_1dt)/S_1$
e.g. for 25-30 mm size group $F_2dt = 1.4(0.5557)(0.2943)/0.9864 = 0.2321$

Column 8 Values of column (7) summed to the middle of each length group
e.g. for 20-25 mm size group $\Sigma(7) = 0+0.0085+0.0626/2 = 0.0398$
(Values in table calculated on computer using more significant figures)

Output Old catch = 388 701 kg New catch = 376 701 % change = -3.1%

Note New catch = $(1 + x/100)\ (\Sigma \frac{S_2 NW}{S_1} \exp \Sigma(F_1dt-F_2dt))$ where $F_2dt = (1 + x/100)\ S_2(F_1dt)/S_1$
and x is the % change in fishing effort.

Column 11 shows the new long-term catches (in this instance in weight terms) obtained by multiplying values in column 2 (representing the initial catches by weight) by the values in column 10 (representing the conversion factors for each length group). The sum of the weights in column 11 provides an estimate of the new long-term catch for comparison with the weight of the catch under the initial conditions.

4.3 Taking account of rejects

It frequently happens that rejection of part of the catch takes place at sea, so that the age or length composition of the landings is not necessarily representative of the age or length composition of the catch. It may further happen, though more rarely, that some proportion of the fish rejected at sea will survive, in which case the numbers caught will over-estimate the numbers effectively removed from the stock and killed. Obtaining reasonable estimates of the numbers discarded in each length group, and their chances of survival is an important, but often neglected, part of the basic data collection system for any fishery. (Estimates within 20-30% would not be unreasonable, and better than is usually available). Assuming information is available, the following section shows how it can be included in the assessment.

Table 7 shows the computations involved to convert estimates of numbers landed to estimates of numbers effectively removed, and killed. Column A shows input data representative of numbers landed. Column B provides estimates of the proportions retained on board vessel for each length group. Column C shows estimates of the numbers caught. For example, for the 25-30 cm length group:

Number caught = $0.21/0.06 = 3.50 \times 10^6$

Column D shows the estimates of the numbers effectively removed from the stock and killed assuming a 30% survival of individuals that are rejected at sea. Computational details of this column are given at the foot of Table 7.

Table 7

Determination of numbers effectively removed from stock, given numbers landed by length group - allowance for rejection at sea

Length group	A No. landed (millions)	B Proportions retained on board ship	C Nos. caught (millions)	D 1/ Nos. removed from stock (millions)
25-30	0.21	0.06	3.50	2.51
30-35	2.46	0.61	4.03	3.56
35-40	2.57	0.99	2.60	2.59
40-45	1.41	1.00	1.41	1.41
45-50	0.71	1.00	0.71	0.71
50-55	0.26	1.00	0.26	0.26
55-60	0.08	1.00	0.08	0.08
$\geq$ 60	0.01	1.00	0.01	0.01

1/ Calculated assuming 30% survival of rejects
e.g., for 25-30 cm length group:
No. of discards = $3.50 - 0.21 = 3.29 \times 10^6$
No. of discards that survive = $3.29 \times 0.3 = 0.99 \times 10^6$
No. effectively removed from stock = $3.50 - 0.99 = 2.51 \times 10^6$

In general (after simplification of steps involved):

Col.D = 0.7 Col.C + 0.3 Col.A.

Estimates of long-term effects of changes in mesh size and/or fishing effort

Estimates of long-term effects of changes in mesh and/or fishing effort can be carried out exactly as in Table 6. The conversion factors (Col.10 in Table 6) can be applied directly either to numbers (or weights) landed or to numbers (or weights) caught, as shown in the example in Table 6. This is permissible provided it is assumed that there is no change in rejection practice (i.e., provided it is assumed that the proportions retained at each length are the same in the new situation as in the old).

Where there is rejection, it is important to use, for the preliminary cohort analysis in Table 5, an input length composition such as that in column D of Table 7. It is this length composition that is required for calculating the value of F_1dt needed for input to Table 6. Thus, if the objective was to determine a new long term length composition for landings (col. A in Table 7) or for catches (col. B) the procedure would be to:

a) determine a length composition such as col. D for input to Table 5, and

b) use col. A, or col. B (converted to weight units if required), as input for col. 2 in Table 6.

4.4 Fisheries in which there is more than one kind of gear

Cohort analysis, and estimates of long-term effects of changes in mesh size and fishing effort, can also be carried out for fisheries in which length composition data are available for different fishing gears or different fleets or countries. An example is given in Tables 8-12. Details of the theory are given by Jones, 1961.

Table 8 shows input length compositions for two countries referred to as gear 1 and gear 2. Also weights caught and mesh sizes in use are given, along with the average weights for each length group.

Cohort analysis (Table 9)

There are two steps:

1. Calculation of values of F_1dt from the total numbers caught. Note that the values under "number caught" are the same as the values in the "total column" of the input data table.

2. Subdivision of values of F_1dt. Values of F_1dt are based on the proportions of the total landings due to that gear, using data from Table 8.

e.g. for the 30-35 cm group

gear 1 $\frac{1850}{4650}$ (0.254) = 0.101

gear 2 $\frac{2800}{4650}$ (0.254) = 0.153

Proportions retained by each gear

Table 10 shows the proportions retained by each gear by length groups.

Values of F_2dt for new mesh (Table 11)

Each value of F_2dt is equal to

$$(1 + \alpha)\ SS_j\ (F_1dt)/S_{ij}$$

where α is the proportional change in fishing effort (= +0.4) in this example.

Table 8

Input Data

Length group / gear cm	Gear 1 thousands	Gear 2 thousands	Total	Average weight (kg)
20-25	1260	-	1260	0.074
25-30	1790	10	1800	0.136
30-35	1850	2800	4650	0.227
35-40	1470	3450	4920	0.352
40-45	977	2023	3000	0.517
45-50	613	823	1436	0.727
50-55	281	329	610	0.989
55-60	166	309	475	1.31
60-65	83	237	320	1.69
65-70	66	175	241	2.14
Actual weight landed (tons)	3000	5000	8000	
mesh size (mm)	60	70		

Table 9

Cohort Analysis

L_∞ = 134 cm M/K = 2.860 Final F/Z = 0.80

Length group cm	Number caught 2/	F_1dt 2/	Subdivision of F_1dt 3/ Gear 1	Gear 2
20-25	1260	0.042	0.042	0
25-30	1800	0.073	0.073	0
30-35	4650	0.254	0.101	0.153
35-40	4920	0.437	0.131	0.306
40-45	3000	0.495	0.161	0.334
45-50	1436	0.447	0.191	0.256
50-55	610	0.336	0.155	0.181
55-60	475	0.465	0.162	0.303
60-65	320	0.664 1/	0.172 1/	0.492 1/
65-70	241	0.664 1/	0.172 1/	0.492 1/

1/ Assuming same values as for 60-65 cm group

2/ Output from cohort analysis

3/ Subdivision of values of F_1dt

e.g. for 35-40 cm group
For gear 1 F_1dt = 0.437 (1470)/4920 = 0.131

For gear 2 F_1dt = 0.437 (3450)/4920 = 0.306

Table 10

Proportions retained by each gear

Length group cm /Gear mesh size	Gear 1 60 (S1j)	Gear 2 70 (S2j)	New mesh size 100 (SSj)
20-25	0.62	0.18	0
25-30	0.97	0.75	0.005
30-35	1.0	1.0	0.147
35-40	1.0	1.0	0.674
40-45	1.0	1.0	0.974
45-50	1.0	1.0	1.0
50-55	1.0	1.0	1.0
55-60	1.0	1.0	1.0
60-65	1.0	1.0	1.0
65-70	1.0	1.0	1.0

Table 11

Values of F_2dt

Length group /Gear cm	Gear 1	Gear 2	Total
20-25	0	0	0
25-30	0	0	0
30-35	0.020	0.032	0.052
35-40	0.124	0.288	0.412
40-45	0.220	0.455	0.675
45-50	0.268	0.358	0.626
50-55	0.217	0.253	0.470
55-60	0.227	0.424	0.651
60-65	0.240	0.689	0.929
65-70 1/	0.240	0.689	0.929

1/ Assuming same values as for 60-65 cm group

For example for 40-45 cm group

For gear 1 0.220 = 1.4 (0.161) (0.974)/1.0
For gear 2 0.455 = 1.4 (0.334) (0.974)/1.0

SS_j = proportion retained by new mesh (100 mm)

and S_{ij} = proportion retained by old mesh for a particular gear (i)

The first two columns of Table 11 give values of F_2dt

e.g. for the 30-35 cm group

gear 1. $1.4(0.147)\ (0.101)/1.0 = 0.020$

gear 2. $1.4(0.147)\ (0.153)/1.0 = 0.32$

etc.

The final column gives Σ (values in cols. 1 and 2)

e.g. for the 30-35 cm group = 0.020 + 0.032
= 0.052

Long-term effects of a change in fishing effort and mesh size (Table 12)

Table 12 shows the computations for determining the long-term effect of a 40% increase in fishing effort, and a change in mesh size for both gears to 100 mm. Columns A-E are similar to computations carried out in Table 6. The new catch (column E) is subdivided, taking account of the relative values of F_2dt for each gear.

Computational details are given at the foot of the table.

5. A SIMPLE GRAPHICAL METHOD OF DETERMINING Z/K

Cohort analysis (and VPA), enable mortality rates to be determined for each length group in a situation where mortality is not necessarily constant with age. A much simpler approach to length composition analysis is to assume that mortality is constant with age and that L_∞ and K are also constant. In this case it is possible to transform the original length composition data in such a way that it can be plotted to give a straight line with a slope of Z/K. Theoretical details are given in Appendix 3 and the method is referred to in a paper by Jones and van Zalinge (in press).

A numerical example is given in Table 13, and Figure 22. Input data in Table 13 consist of a length composition of numbers caught. These are first converted to cumulative catches (column A). Column B shows the values of $L_\infty - L$ for each length group. When the logarithms of the cumulative catches are plotted against the logarithms of the values of $L_\infty - L$, a relationship is obtained which is linear over a considerable part of its range (Fig.22). The slope of this line, which in this example = 3.30, is an estimate of Z/K.

In practice there may be a departure from linearity at either end of the curve. At the end of the curve that corresponds to the larger individuals, this is likely to be due to variations in the growth rates of large individuals (i.e., the fact that some large individuals may be growing whereas others may have stopped growing altogether). At the end of the curve that corresponds to the smallest individuals, non-representative sampling often due to selectivity may cause catches to be unrepresentative of numbers in the sea. This is clearly shown in Fig.22.

As a first approximation, however, the linear part of the curve may be used to provide a first estimate of Z/K for any input value of L_∞. Different values of Z/K may be then obtained for different values of L_∞. If just one growth increment is available, the procedure described in Section 3.7 can be used to find a value of K consistent with the growth increment and the chosen value of L_∞. Values of Z as well as Z/K can then be obtained for different values of L_∞.

Table 12

Effect of 40% increase in effort and change in mesh size to 100 m

Length group	A $\Sigma F_1 dt$	B $\Sigma F_2 dt$	C $e^{(A-B)}$	D old catch	E new catch (numbers)	Subdivision of new catch Gear 1	Gear 2	Average weight (kg)
20-25	0.021	0	1.021	1.260	0	0	0	0.074
25-30	0.078	0	1.081	1.800	0	0	0	0.136
30-35	0.242	0.026	1.241	4.650	1.181	455	726	0.227
35-40	0.587	0.258	1.390	4.920	6.448	1.941	4.507	0.352
40-45	1.053	0.801	1.287	3.000	5.265	1.716	3.449	0.517
45-50	1.524	1.452	1.075	1.436	2.162	926	1.236	0.727
50-55	1.916	2.000	0.919	610	784	326	422	0.989
55-60	2.316	2.560	0.783	475	521	182	339	1.31
60-65	2.881	3.350	0.626	320	280	72	208	1.69
65-70	3.545	4.280	0.480	241	162	42	120	2.14

	Old yield	New yield	% Change
Gear 1	3000	3155	+ 5
Gear 2	5000	5904	+ 18
All gears	8000	9109	+ 14

Notes

A Values of $F_1 dt$ for all gears summed to the middle of each length group
e.g., for the 30-35 cm group 0 + 0.042 + 0.073 + 0.254 (0.5) = 0.242

B Values of $F_2 dt$ for all gears summed to the middle of each length group
e.g., for the 30-35 cm group 0 + 0 + 0.052 (0.5) = 0.026

C The factor $e^{(A-B)}$ represents the long-term effect of the changes in effort and mesh size on the stock in each length group

D Values from input data table

E $F_2 dt$ (Col.D) (Col.C)/$F_1 dt$
e.g., for the 30-35 cm group 0.052 (4650) (1.241)/0.254 = 1181

Subdivision of new catch is based on the relative values of $F_2 dt$ for each gear
e.g., for the 30-35 cm group
Gear 1 0.02 (1181)/0.052 = 455
Gear 2 0.032 (1181)/0.052 = 726

New Yield = Sum of products of new catches and weights, e.g., for Gear 1
(0 x 0.074) + (0 x 0.136) + (455 x 0.227) + - - - - - - - - - = 3155

Long term % change for Gear 1 = 100 (3155 - 3000)/3000 = +5%

Table 13

Determination of Z/K from cumulative length composition data

Length group (cm)	Number caught (thousands)	A Cumulative numbers (CN)	L 1/	B L_∞ - L 2/	ln (Col.A)	ln (L_∞ - L)
40-43	25	1750	40	20	7.47	3.00
43-46	133	1725	43	17	7.45	2.83
46-49	618	1529	46	14	7.37	2.64
49-52	793	974	49	11	6,88	2.40
52-55	170	181	52	8	5,20	2.08
55-58	11	11	55	5	2.40	1.61
TOTAL	1750					

1/ L = length at lower end of length group

2/ Determined using a value of L_∞ = 60 cm

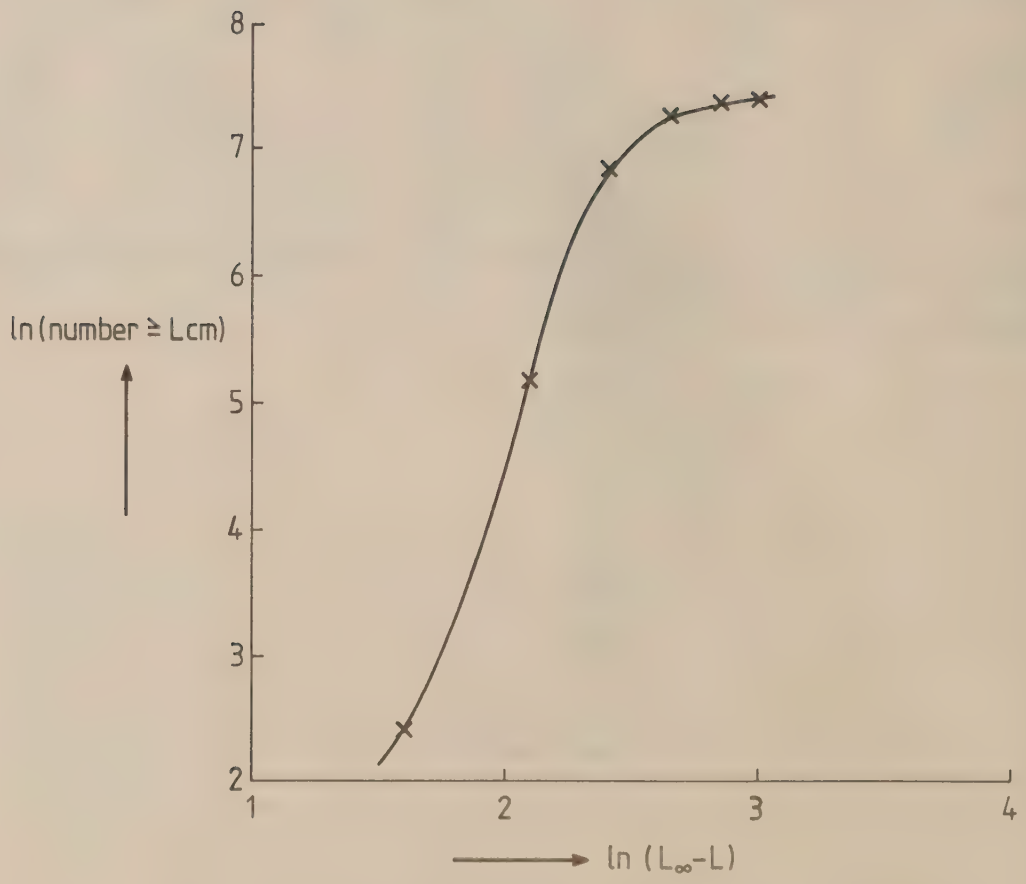


Fig.22 When the logarithms of numbers ≥L are plotted against the logarithms of (L_∞ - L) the resultant relationship should be linear over at least the central part of its range. The slope of this linear portion is equal to Z/K.

APPENDIX 1

Virtual Population Analysis (VPA)

The object of Virtual Population Analysis is to determine the numbers of individuals that must have been present in the sea, to account for a known sustained catch, and to take account also of losses due to natural causes. It is assumed that information about catch is available by age groups, and that within any one age group the decline in numbers in the stock, with time, can be represented by an exponential curve with a constant mortality rate. It is not necessary to assume that the mortality rate is the same from one age group to the next however. An example is given in Table 14 using the same input data as were used in Table 1, i.e., the age composition of the catch is the same, as are also the input values of M (0.2) and F for the oldest age group ($F_8 = 0.2$). Computational details based on Gulland (1965) are given at the foot of the table. The procedure differs from cohort analysis in that the computations cannot be made directly and that, at each step, an equation has to be solved either iteratively or with the use of a table. For the purpose of this example solutions are obtained using Table 15, taken from Schumacher, 1970.

The method uses the following relationships:

$$E_t = A_t + e^{-Z}t\ E_{t+1} \quad \text{for all except the oldest age group}$$

$$Q_t = e^{-Z}t/A_t = V_{t+1}/C_t\ E_{t+1}$$

$$A_t = F_t\ (1 - e^{-Z}t)/Z_t$$

Where E_t is the proportion of fish alive at the beginning of the t^{th} age group that are subsequently captured. E_t is defined in terms of the virtual population at age t years (V_t), thus:

$$V_t = E_t\ N_t$$

where N_t is the number alive at the beginning of the t^{th} age group.

At each step in the calculation a value of Q_t is calculated from the relationship:

$$Q_t = V_{t+1}/C_t\ E_{t+1}$$

A value of Z_t is then found iteratively (or using the values in Table 15) to satisfy the relationship:

$$Q_t = e^{-Z}t/A_t$$

To a first approximation the results obtained in Table 14 are the same as those obtained using the cohort approximation in Table 1.

Oldest age group (T) consisting of individuals aged T and older

In the example above the oldest age group (T) consists of individuals aged T and older. The value of E_t for the oldest age group was calculated from the relationship

$$E_t = F_t/Z_t$$

as shown in Table 14.

Oldest age group (T) consisting of individuals aged T only

If the oldest age group consists of fish aged T only, the value of E_t is equivalent to the value of A_t. For example, if, in Table 14, the 85 individuals had belonged to the age group 8-9 years, the value of E_8 would have been calculated from the expression:

$$E_8 = 0.2 \ (1 - e^{-0.4}) \ /0.4$$

Subsequent calculations would then have been as in Table 14.

Table 14

Virtual population analysis. Oldest age group (T) consisting of fish aged T and older

Age group (t)	Numbers landed (C_t)	V_t	E_t	e^{-Z_t}	A_t	Q_t	Z_t	F_t	N_t
1	867	5807	0.581	0.741	0.086	8.530	0.30	0.10	9995
2	1732	4940	0.668	0.607	0.236	2.601	0.50	0.30	7395
3	1612	3208	0.712	0.497	0.360	1.398	0.70	0.50	4506
4	931	1596	0.708	0.449	0.413	1.087	0.80	0.60	2254
5	362	665	0.657	0.497	0.360	1.400	0.70	0.50	1012
6	153	303	0.598	0.549	0.301	1.82	0.60	0.40	507
7	65	150	0.540	0.607	0.236	2.61	0.50	0.30	278
8 & older	85	85	0.5				0.4	0.2	170

Assumed values: $M = 0.2$ $F_8 = 0.2$

1. Calculate $V_t = \Sigma C_t$ summed from the oldest age group, e.g. 150 = 85 + 65 etc.
2. Calculate E_t for the oldest age group from F_t/Z_t e.g. $E_8 = 0.2/0.4 = 0.5$
3. Calculate values of $Q_t = V_{t+1}/C_t\ E_{t+1}$

   e.g. $Q_7 = 85/65(0.5) = 2.615$
4. Locate the value of Q in Table 15 and read off values of A, e^{-Z}, Z and F

   e.g. $A_7 = 0.236$, $e^{-Z} = 0.607$ etc.
5. Calculate $E_t = A_t + E_{t+1}\ e^{-Z_t}$

   e.g. $E_7 = 0.236 + 0.5\ (0.607) = 0.540$
6. Continue until all columns (except N_t column) are complete
7. Calculate N_t at each age from $N_t = V_t/E_t$

   e.g. $N_5 = 66.5/0.657 = 1012$

Summary: $Q_t = V_{t+1}/C_t\ E_{t+1} = e^{-Z}t/A_t$

For oldest age group: $E_t = F_t/Z_t$

For younger age groups: $E_t = A_t + E_{t+1}\ e^{-Z_t}$

$N_t = V_t/E_t$ $\qquad$ $A_t = F_t\ (1-e^{-Z}t)/Z_t$

Table 15

Table for use in Virtual population estimation when M = 0.2

From Schumacher (1970)

F	Z	e^{-Z}	$\frac{A_t}{F}(1-e^{-Z})$	$\frac{Q_t}{Ze^{-Z}}(1-e^{-Z})$	F	Z	e^{-Z}	$\frac{A_t}{F}(1-e^{-Z})$	$\frac{Q_t}{Ze^{-Z}}(1-e^{-Z})$	F	Z	e^{-Z}	$\frac{A_t}{F}(1-e^{-Z})$	$\frac{Q_t}{Ze^{-Z}}(1-e^{-Z})$
0.01	0.21	0.811	0.009	90.1	0.46	0.66	0.517	0.337	1.534	0.91	1.11	0.330	0.550	0.600
0.02	0.22	0.803	0.018	44.6	0.47	0.67	0.512	0.343	1.493	0.92	1.12	0.326	0.553	0.590
0.03	0.23	0.795	0.027	29.4	0.48	0.68	0.507	0.348	1.457	0.93	1.13	0.323	0.557	0.580
0.04	0.24	0.787	0.036	21.9	0.49	0.69	0.502	0.354	1.418	0.94	1.14	0.320	0.561	0.570
0.05	0.25	0.779	0.044	17.7	0.50	0.70	0.497	0.360	1.381	0.95	1.15	0.317	0.565	0.561
0.06	0.26	0.771	0.053	14.5	0.51	0.71	0.492	0.365	1.348	0.96	1.16	0.313	0.568	0.551
0.07	0.27	0.763	0.061	12.5	0.52	0.72	0.487	0.371	1.313	0.97	1.17	0.310	0.572	0.542
0.08	0.28	0.756	0.070	10.8	0.53	0.73	0.482	0.376	1.282	0.98	1.18	0.307	0.575	0.534
0.09	0.29	0.748	0.078	9.59	0.54	0.74	0.477	0.382	1.249	0.99	1.19	0.304	0.579	0.525
0.10	0.30	0.741	0.086	8.62	0.55	0.75	0.472	0.387	1.220	1.00	1.20	0.301	0.582	0.517
0.11	0.31	0.733	0.095	7.72	0.56	0.76	0.468	0.392	1.194	1.01	1.21	0.298	0.586	0.509
0.12	0.32	0.726	0.103	7.05	0.57	0.77	0.463	0.398	1.163	1.02	1.22	0.295	0.589	0.501
0.13	0.33	0.719	0.111	6.48	0.58	0.78	0.458	0.403	1.136	1.03	1.23	0.292	0.593	0.492
0.14	0.34	0.712	0.119	5.98	0.59	0.79	0.454	0.408	1.113	1.04	1.24	0.289	0.596	0.485
0.15	0.35	0.705	0.127	5.55	0.60	0.80	0.449	0.413	1.087	1.05	1.25	0.287	0.599	0.479
0.16	0.36	0.698	0.134	5.21	0.61	0.81	0.445	0.418	1.065	1.06	1.26	0.284	0.603	0.471
0.17	0.37	0.691	0.142	4.87	0.62	0.82	0.440	0.423	1.040	1.07	1.27	0.281	0.606	0.464
0.18	0.38	0.684	0.150	4.56	0.63	0.83	0.436	0.428	1.019	1.08	1.28	0.278	0.609	0.456
0.19	0.39	0.677	0.157	4.31	0.64	0.84	0.432	0.433	0.998	1.09	1.29	0.275	0.612	0.449
0.20	0.40	0.670	0.165	4.06	0.65	0.85	0.427	0.438	0.975	1.10	1.30	0.273	0.616	0.443
0.21	0.41	0.664	0.172	3.86	0.66	0.86	0.423	0.443	0.955	1.11	1.31	0.270	0.619	0.436
0.22	0.42	0.657	0.180	3.65	0.67	0.87	0.419	0.447	0.937	1.12	1.32	0.267	0.622	0.429
0.23	0.43	0.651	0.187	3.48	0.68	0.88	0.415	0.452	0.918	1.13	1.33	0.264	0.625	0.422
0.24	0.44	0.644	0.194	3.32	0.69	0.89	0.411	0.457	0.899	1.14	1.34	0.262	0.628	0.417
0.25	0.45	0.638	0.201	3.17	0.70	0.90	0.407	0.462	0.881	1.15	1.35	0.259	0.631	0.410
0.26	0.46	0.631	0.208	3.03	0.71	0.91	0.403	0.466	0.865	1.16	1.36	0.257	0.634	0.405
0.27	0.47	0.625	0.215	2.91	0.72	0.92	0.399	0.471	0.847	1.17	1.37	0.254	0.637	0.399
0.28	0.48	0.619	0.222	2.79	0.73	0.93	0.395	0.475	0.832	1.18	1.38	0.252	0.640	0.394
0.29	0.49	0.613	0.229	2.68	0.74	0.94	0.391	0.480	0.815	1.19	1.39	0.289	0.643	0.387
0.30	0.50	0.607	0.236	2.57	0.75	0.95	0.387	0.484	0.800	1.20	1.40	0.247	0.646	0.382
0.31	0.51	0.600	0.243	2.47	0.76	0.96	0.383	0.489	0.783	1.21	1.41	0.244	0.649	0.376
0.32	0.52	0.595	0.250	2.38	0.77	0.97	0.379	0.493	0.769	1.22	1.42	0.242	0.651	0.372
0.33	0.53	0.589	0.256	2.30	0.78	0.98	0.375	0.497	0.755	1.23	1.43	0.239	0.654	0.365
0.34	0.54	0.583	0.263	2.22	0.79	0.99	0.372	0.501	0.743	1.24	1.44	0.237	0.657	0.361
0.35	0.55	0.577	0.269	2.14	0.80	1.00	0.368	0.506	0.727	1.25	1.45	0.235	0.659	0.357
0.36	0.56	0.571	0.276	2.07	0.81	1.01	0.364	0.510	0.714	1.26	1.46	0.232	0.663	0.350
0.37	0.57	0.566	0.282	2.01	0.82	1.02	0.361	0.514	0.702	1.27	1.47	0.230	0.665	0.346
0.38	0.58	0.560	0.288	1.94	0.83	1.03	0.357	0.518	0.689	1.28	1.48	0.228	0.668	0.341
0.39	0.59	0.554	0.295	1.88	0.84	1.04	0.353	0.522	0.676	1.29	1.49	0.225	0.671	0.335
0.40	0.60	0.549	0.301	1.82	0.85	1.05	0.350	0.526	0.665	1.30	1.50	0.223	0.674	0.331
0.41	0.61	0.543	0.307	1.77	0.86	1.06	0.346	0.530	0.653					
0.42	0.62	0.538	0.313	1.72	0.87	1.07	0.343	0.534	0.642					
0.43	0.63	0.533	0.319	1.67	0.88	1.08	0.340	0.538	0.632					
0.44	0.64	0.527	0.325	1.62	0.89	1.09	0.336	0.542	0.620					
0.45	0.65	0.522	0.331	1.58	0.90	1.10	0.333	0.546	0.610					

APPENDIX 2

Determination of the long-term effect of a change in fishing effort and mesh size (based on Jones, 1961)

Catch before change

Under equilibrium conditions, the number of fish landed in a particular length group can be written, as a first approximation, in the form:

$$C_j = Rr_j(F_1dt)_j \exp - (\sum_j^{} (F_1dt)_j + M_j)$$

where C_j = number landed from length group j

M_j is the cumulative natural mortality up to the middle of length group j.

R = number of recruits to smallest length group

r_j = proportion of fish in length group j that are retained on board

$(F_1dt)_j$ is the value of F_1dt for length group j

F_1 is the instantaneous fishery mortality rate for length group j before the change in effort or mesh size.

dt is the length of time required to grow from the smallest to the largest size in length group j.

Values of F_1 and dt are not known. However, estimates of their product, $(F_1dt)_j$, can be obtained directly from a cohort analysis of the length composition data, assuming the observed length frequency distribution is representative of the length frequency distribution under equilibrium conditions.

The summation $\sum_j (F_1dt)_j$ is the sum of values of $(F_1dt)_j$ for all length groups from the smallest length group to the middle of the length group j, i.e., to a first approximation

$$\sum_j^3 (F_1dt)_j = (F_1dt)_1 + (F_1dt)_2 + 0.5\ (F_1dt)_3$$

Catch after change

Assuming no change in recruitment or rejection practice, the new equilibrium landings after a change in effort and mesh size can be written:

$$C'_j = Rr_j(F_2dt)_j \exp - (\sum_j^{} (F_2dt)_j + M_j)$$

where $(F_2dt)_j$ is the new value of $(F_1dt)_j$ for length group j.

$$(F_2dt)_j = (1 + \alpha)\ SS_j\ (F_1dt)_j/S_j$$

where α = proportional change in fishing effort

S_j = proportion retained by length group j before the change in mesh size

SS_j = proportion retained for length group j after the change in mesh size.

Ratio of new catch to old catch

Assuming no change in recruitment or rejection practice, or natural mortality rates, the ratios of the new to the old landings for catches are given by:

$$C'_j/C_j = (F_2dt)_j \ (\exp - (\sum_j((F_1dt)_j - (F_2dt)_j))/(F_1dt)_j$$

Calculating the new landings (or catches)

After the change, the new landings (or catch) in weight for each length group j can be calculated from:

$$N_j \ W_j \ C'_j/C_j \quad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where N_j is the original landings (or catch) in numbers for length group j before the change.

W_j is the average weight of a fish in length group j (assumed to be the same before and after the change).

Equation (1) is equivalent to:

$$N_j \ W_j \ (F_2dt)_j \ (\exp -(\sum_j \ ((F_1dt)_j - (F_2dt)_j))/(F_1dt)_j \quad \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

APPENDIX 3

Derivation of a formula for determining the numbers ⩾ a given length under steady state conditions

Assumptions

1. Constant mortality with age

2. Individual growth curves following von Bertalanffy curves with same values of L_∞ and K, but not necessarily same values of t_o.

Let $N_t dt = R \exp(-Zt)\, dt$

where $N_t dt$ = number in the cohort with ages in the range $t \pm \frac{1}{2} dt$

R = initial number when t = o

Z = instantaneous mortality rate due to all causes

The number of individuals in the sea ⩾ a specified age (t) is then given by

$$R \int_t^\infty \exp - (Zt)dt = (R \exp(-Zt))/Z \qquad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Let the relationship between length (L) and age (t) be determined by the von Bertalanffy growth equation

i.e. $L = L_\infty (1 - \exp(-K(t-t_o)))$

Then re-arrangement of terms leads to:

$$t = t_o - \frac{1}{K} \ln \{(L_\infty - L)/L_\infty\}$$

Substituting for t in (1) gives the number in the sea ⩾ L ($\sum_L^\infty N$) as:-

$$\sum_L^\infty N = C\,(L_\infty - L)^{Z/K} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

where C is a term that is independent of L

This equation can be made linear by taking logarithms of both sides, i.e.

$$\ln \sum_L^\infty N = \frac{Z}{K} \ln (L_\infty - L) + \ln C \qquad \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

This suggests that by plotting the natural logarithms of the numbers ⩾ L against the logarithms of $(L_\infty - L)$, one should obtain a straight line with a slope of Z/K.

Since constant mortality with age is assumed, it follows that the length composition of the numbers caught should be representative of the length composition of the numbers in the sea. The technique should therefore be applicable to the length compositions of either catches per unit effort, or of catches.

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